Ref. Ares(2016)2069778 - 30/04/2016

D6.1 - Analysis of different potential configurations of non-rigid inter-moored devices

DATE:

April 2016

PROJECT COORDINATOR:

WavEC Offshore Renewables

RESPONSIBLE FOR DELIVERABLE:

Plymouth University

GRANT AGREEMENT NR: 641334

PROJECT: WETFEET

The WETFEET – Wave Energy Transition to Future by Evolution of Engineering and Technology project has received funding from the European Union's Horizon 2020 programme under grant agreement No 641334.

Report on analysis of different potential configurations of non-rigidly inter-moored devices in what concerns loads, motions, risk of collision and performance			
Project	WETFEET – Wave Energy Transition to Future by Evolution of Engineering and Technology		
WP No.	6	WP Title	Array breakthrough: Sharing Moorings (and Electrical Cables)
Deliverable No.		6.1	
Nature (R: *Report*, P: *Prototype*, O: *Other*)		R	
Dissemination level (PU, PP, RE, CO)		PU	
Lead beneficiary:		Plymouth University	
Contributing partners		WavEC, IST, INNOSEA, Aurora Ventures	
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Quality reviewer		Aurora Ventures, WavEC	
Status (F: final; D: draft; RD: revised draft):		F	
Due Delivery Date:		30/04/2016	
Actual Delivery Date:		30/04/2016	

Version no.	Dates and comments
1	10-Feb-2016 Deliverable structure defined
2	First Draft
3	Restructured draft sent to all WP partners
4	§5 & §6 merged, including comments and revisions from INNO and Aurora
5	Comments from WavEC addressed

Executive Summary

The wave energy sector has many technological hurdles to overcome before commercial viability can be achieved, among them reliability; survivability; device efficiency and cost. The WETFEET project aims to address some of these issues and provide industry guidance to increase momentum in the sector. This document describes Task 6.1.1 of WP6 and addresses the assessment of potential configurations of non-rigid inter-moored arrays. The goal of WP6 is to determine whether cost savings can be achieved with component sharing and what the implications on survivability, performance, the environment and sea-space utilisation are.

The OWC spar buoy has been chosen as an example device with a proposed site off Leixões, Portugal to allow environmental loading to be considered. The mooring design used in this deliverable was described in D2.1 and generic mooring components were used to assess the costs for the inter-device lines.

Three array layouts are proposed: a linear staggered, a pentagon and a die configuration, and the implications of progressively increasing the level of interconnection between the devices are examined. The evaluation of the proposed layouts is summarised here:

- Array performance is discussed in terms of device interaction
- Survivability examines the array spacing required to prevent collisions based on the array layout and spacing using a simple statics approach
- Line tension under environmental loading is estimated
- Cost is assessed by considering mooring line component costs, electrical cable architecture costs and installation cost
- Environmental impacts are discussed and the sea-space utilisation is quantified
- Experimental and numerical modelling considerations are also discussed

The report demonstrates that there is a potential for cost saving through shared components and device interconnection and examples of possible configurations to be examined in subsequent tasks of the WP are presented.

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List of acronyms and abbreviations

AC/DC	Alternating current/direct current
bhp	Brake horsepower
CAPEX	Capital expenditure
D	Deliverable
DOF	Degree(s) of freedom
EIA	Environmental impact assessment
hp	Horsepower
IST	Instituto Superior Técnico
kts	Knots
LCOE	Levelised cost of energy
MDD	Motion-dependent device
O&M	Operations and maintenance
OPEX	Operating expenditure
OWC	Oscillating Water Column
PTO	Power take-off (device)
SWL	Still water level
WEC	Wave energy converter
WP	Work package

List of symbols

C_d	Coefficient of drag
C_m	Coefficient of mass
D	Device diameter
E/T_0h	Non-dimensional mooring damping
F	Force
g	Acceleration due to gravity
H_{max}	Maximum wave height
H_s	Significant wave height
h	Water depth
k_0	wave number
L	Line length
L_E	Environmental load
N	Number of devices
P	Power
$\bar{q}$	Interaction factor
S	Variance spectral density
T	Tension (with numeric subscripts)
T_{max}	Maximum wave period
u	Particle velocity
$\dot{u}$	Particle acceleration
x_S	Horizontal projected length of slack mooring line
x_T	Horizontal projected length of taut mooring line
β	Wave heading angle
Δx	Difference of projected lengths of mooring line
ρ	Fluid density
ω	Wave frequency

1 Introduction

The wave energy industry is currently held back by numerous technological issues relating to reliability, survivability and high development and operational costs. Within the framework of the WETFEET H2020 EU-funded project, a set of breakthroughs has been identified to address the obstacles that have been delaying the path towards commercialization of the wave energy sector. The WETFEET project aims to create breakthroughs in four areas: survivability; operation and maintenance (O&M); power take-off devices (PTO) and arrays. This will be achieved using two devices as case studies: the Symphony, developed by Teamwork Technology, and the oscillating water column (OWC) spar buoy developed by Instituto Superior Técnico (IST), Lisbon. These two devices were chosen as they represent two different technology types that both show promising results and as such, the outcomes of this project will be applicable to a range of devices [1].

An increase in energy yield per unit area of seabed has been shown to have many financial and environmental benefits [2], therefore to improve the commercial attractiveness of wave energy extraction, arrays of devices need to be considered. However, with moorings, O&M and installation accounting for between 40% and 45% of project life costs, the high capital costs involved in array deployment is reducing the attractiveness of investment into the sector [3, 4].

Shared moorings have already been investigated for the aquaculture industry to expand capacity in open ocean-deployed fish cages. The mooring grid securing four 3000 m^3 fish cages shown in Figure 1-1, was successfully deployed in the Gulf of Maine for seven years (2003 – 2010) with no structural integrity issues or structure losses [5]. Even though this was in a less energetic sea state than the one in which a WEC array might be deployed, it is a first step towards fully-developed shared mooring systems.

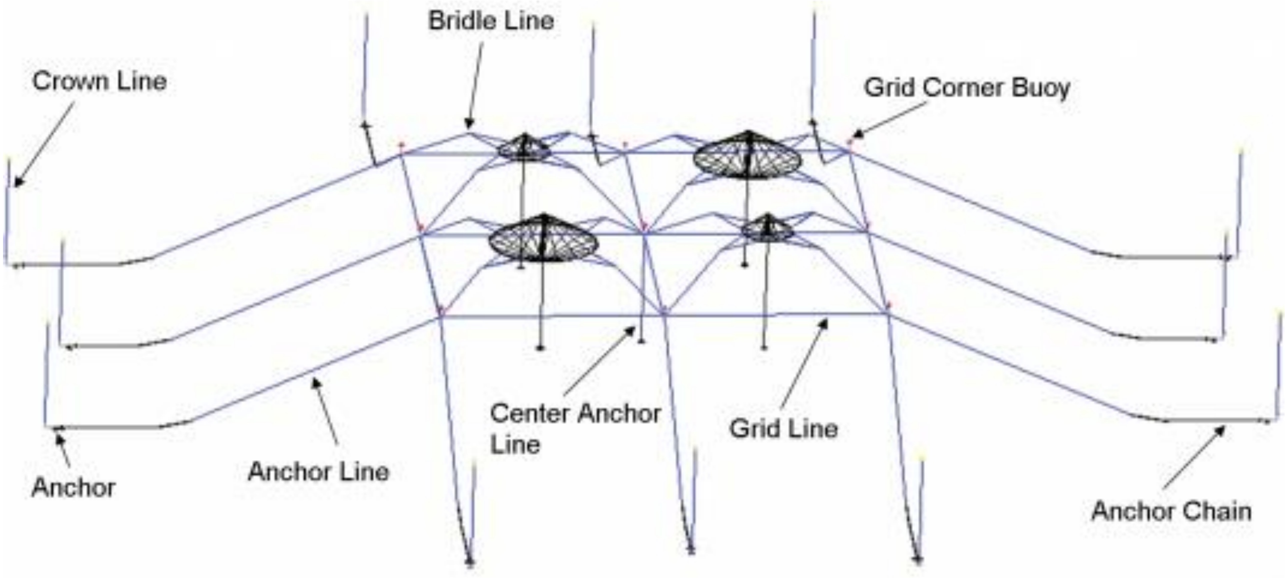


FIGURE 1-1 A SUBMERGED GRID MOORING CAPABLE OF SECURING FOUR FISH CAGES REDUCING THE NUMBER OF ANCHORS REQUIRED BY 19% [6].

As claimed in the patent EP1993901 B1 [7], transfer of this technology to wave energy converter arrays could be utilised in order to:

- Reduce the cost associated with the number of anchors required
- Reduce the cost associated with the number of seabed-fixed mooring lines
- Increase the energy yield per unit area of seabed
- Reduce installation costs

However, many wave energy converters are classified as motion-dependent devices (MDD), for which power extraction is a function of the device motion. Thus, if devices share moorings, complex motion coupling between devices may occur. This coupling needs to be understood in order to assess if the cost saving associated with anchor and mooring line reduction is greater than any performance reduction that may occur.

The aim of Work Package 6 is to identify and quantify the potential for sharing mooring lines within an array as a cost, environmental impact and ocean space utilisation reduction strategy, but also to consider any potential performance enhancements. The goals of this work package will be achieved through a series of tasks undertaken by the partners. Conceptually, these can be split into two stages, as illustrated in Figure 1-2, namely the planning stage (Task 6.1), in which the array configurations to be investigated are selected and the criteria for evaluating them established, and the performance assessment stage (Tasks 6.2 –6.4). In the performance assessment stage, the effect on performance (power production) and survivability (mooring loads and device excursions) of deployment in rigid and non-rigid inter-moored arrays will be assessed through a programme of numerical modelling and laboratory scale testing. Task 6.1 leads to two deliverables: D6.1 (this report) covering the

feasibility analysis of a non-rigidly inter-moored array and D6.2, covering the feasibility analysis of different potential configurations of rigidly inter-moored devices. Subsequent tasks in this work package are the building of physical and numerical models, and the basin testing of the chosen arrays. This work package will culminate in D6.5: Design guidance on the use of shared moorings, to be delivered in month 32 of the project. The full cost evaluation of all the breakthroughs proposed in WP2 – WP6 will be addressed in WP7 Multi-disciplinary assessment for large-scale deployment.

This report describes the steps taken to select and evaluate the potential configurations of the flexibly-moored arrays to be studied in WP6. Section 2 gives a brief introduction to what is meant by an array. It also describes motivations for constructing an array of devices and potential problems associated with WEC arrays. Some popular components of a mooring system are described in Section 3. The initial configurations proposed as part of this work package are described in Section 4 and two different approaches of inter-connection are discussed, along with the ramifications for the goals of the Work Package. Section 5 discusses the criteria used to assess the proposed configurations and the results of the assessment presented. The constraints imposed by the other tasks in this Work Package are considered in Section 6 together with their effect on the configuration selection. A final recommendation as to the configuration of the non-rigidly inter-moored array of devices is given in Section 7.

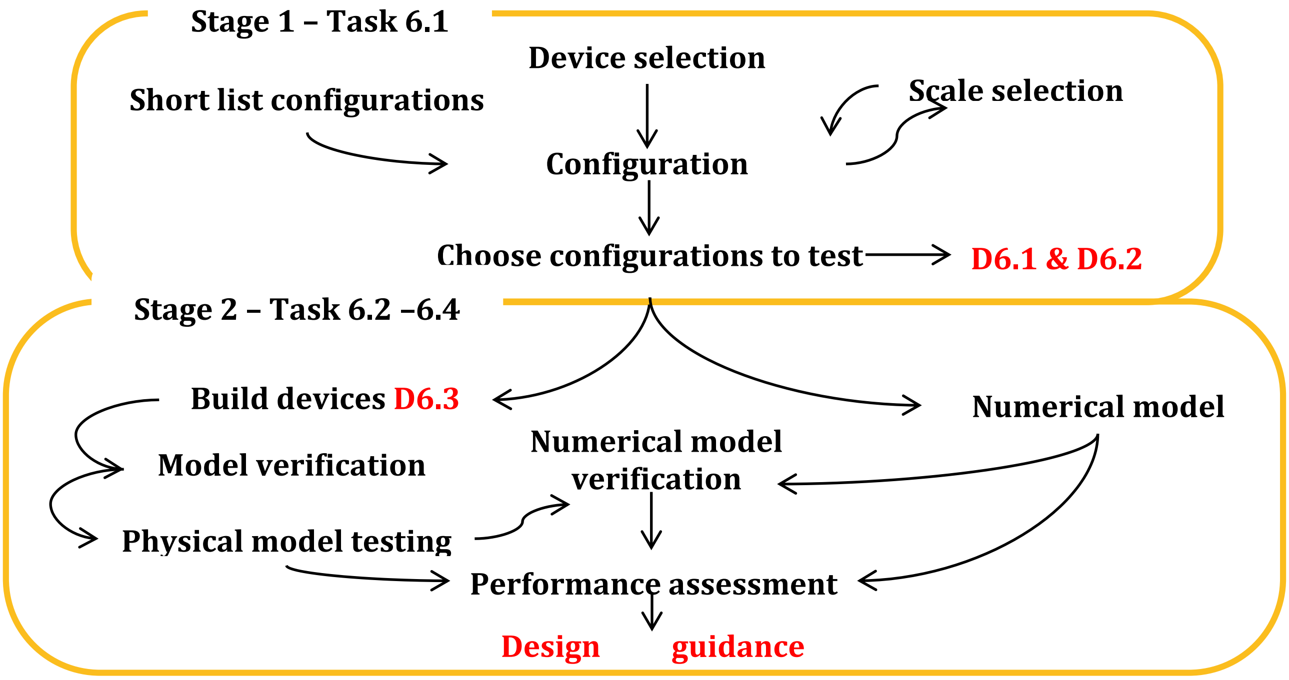


FIGURE 1-2 WORK PACKAGE 6 CAN BE SPLIT INTO TWO DISTINCT STAGES. THIS REPORT, D6.1, ALONG WITH ITS PARTNER DELIVERABLE D6.2, COVERS THE TASKS IN STAGE 1.

In the selection of the configurations to be tested, little emphasis is placed on the electrical cable architecture. This is primarily because the cables will not form part of the experimental modelling and this is discussed further in Section 6.

It must be noted that the aim of WP6 Task 6.1, reported here, is not to suggest the best mooring system for the chosen device, nor is it to suggest the optimum array geometry, or test site. The aim is to select configurations worthy of physical and numerical modelling that are likely to lead to implementable lessons in the design and engineering of arrays of devices.

2 Array definition

A WEC array is a collection of wave energy devices in close proximity working in series or parallel to convert wave energy to electricity. The principal aim of an array is to lower energy costs, which can be achieved through economies of scale for building, installation and maintenance, and through the sharing of some systems inside the array, such as electrical or mooring systems [8]. With many WEC designs still to be proven on a small scale, smaller arrays are preferred in order to limit the costs [9].

The EU-funded EquiMar project defined different types of array by size, which is linked to the purpose of the array, Table 2-1. Demonstrator arrays should be considered for the first deployments and only this size of array will be discussed in this report. Larger arrays are likely to be more complex and to include more interference effects [10].

TABLE 2-1 ARRAY TYPES AS A FUNCTION OF NUMBER DEVICES, PURPOSE AND DEVICE READINESS [10].

Array type	No. of devices	Purpose of array	Device design
Demonstrator	<10	Demonstration of availability, grid connection. Trial of installation methods for multiple deployments.	Utilisation of design used for sea trials (good understanding) with technical modifications depending upon sea trials.
Small	10 – 50	Up-scaling to small commercial arrays. Proof of cost reduction through scale and evolution of components.	Device evolution from designs used at sea trial and demonstrator array stages. Potential for improved reaction and hydrodynamic subsystems. Modifications to control and PTO
Medium	50 – 200	Cost reduction to upper end of grid system prices, payback existing energy generation technologies.	Device approaching a more stabilised design for metocean conditions not far removed from previous array stage. Modified for more economical deployment and O&M.
Large	>200	Generation costs competitive with existing technologies. Use of evolved components, device designs, deployment and O&M methods.	Next generation device designs. Arrays moving to more challenging and energetic sites. Potentially very different technology employed especially reaction subsystem, deployment and O&M methods.

In addition, device arrays can be split into first and second generations, based on their complexity [10]:

First-generation arrays

- Single row of devices perpendicular to the incoming wave with the possibility of a second row with devices staggered relative to the first row
- Permit access to all devices from outside the array
- Minimise device interaction
- Allow the deployment of a large array
- Distances between the devices have to be chosen to limit device interaction
- Distances depend on device type and wave climate
- Early arrays will inform later designs

Second-generation arrays

- More than two rows of devices and a large number of devices
- Interaction effects may lead to a reduced performance
- More likely to be used for a small array type or bigger (medium, large) type

First-generation arrays can already achieve a reasonable installed capacity and so they are currently still more likely to be built than second-generation arrays, which are not yet fully developed [8]. Once a specific WEC technology is proven, it will be important to increase the array density by reducing the distance between devices, in particular for devices with a low power capacity. This will reduce the costs of interconnecting power cables and optimise the sea space utilisation [10].

A primary benefit of arrays is that total instantaneous power will be the sum of the power produced by each unit in the array. With the units being placed a certain distance away from each other, the incident waves will impact the devices at different times. This means that total array power production will be smoothed by the addition of units into the array.

3 Mooring types

A number of mooring options are available in order to station the array, with extensive experience coming from the oil and gas, and shipping industries. Owing to the motion-dependent nature of wave energy devices, a holistic system approach needs to be considered when selecting a mooring type.

Three categories of mooring can be defined: passive, used for station keeping only; active, which has a significant influence on the mooring dynamics and is common for WECs; and reactive, in which the mooring is part of the system [4]. Typical active mooring types for WECs are shown in Figure 3-1 and these are described below.

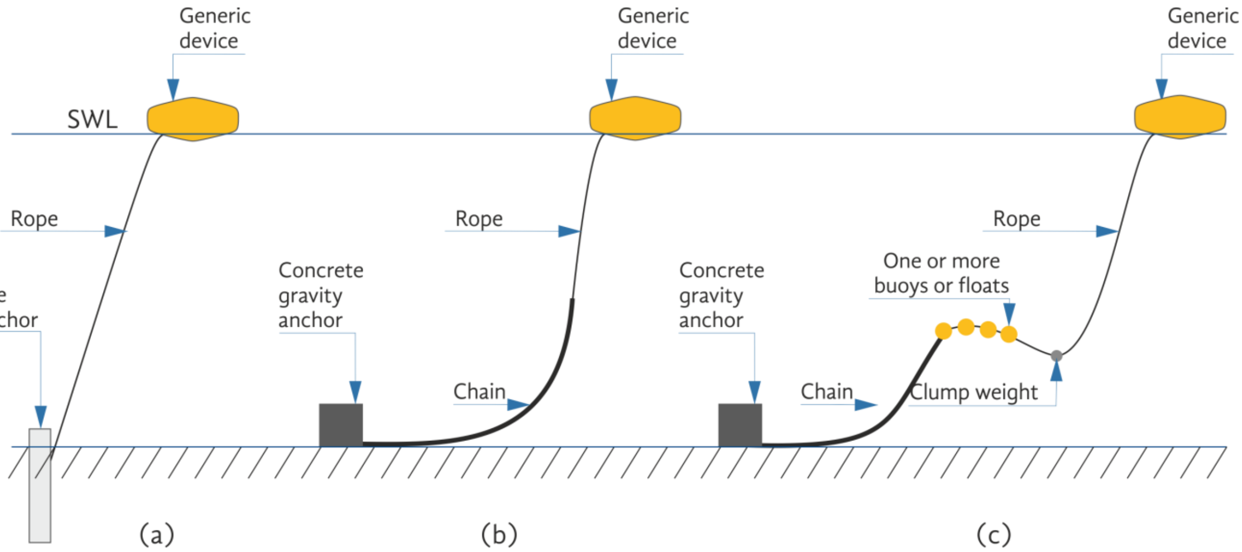


FIGURE 3-1 THREE TYPES OF MOORING USED FOR WECS: (A) TAUT MOORINGS; (B) CATENARY MOORINGS AND (C) COMBINED S-SHAPE MOORINGS. FOR CLARITY, ONLY ONE MOORING LINE PER DEVICE IS SHOWN EVEN IF MULTIPLE LINES WOULD BE MORE APPROPRIATE FOR A SPECIFIC DEVICE.

3.1 Taut mooring

Taut mooring systems have been used in the offshore industry in the form of Tension Leg Platforms (TLPs), in which the lines are pre-tensioned to ensure they do not go slack. For WECs, taut moorings connecting the float the seabed are used to keep the device on station and to restrict motions, Figure 3-1 (a). The tension in the lines is caused by a combination of the pre-tension and the forces on the connected device. Taut moorings result in a small footprint with many degrees of freedom constrained. Owing to the vertical loading on the seabed connection point, this mooring type often results in expensive anchor systems and costly installation procedures. Since the lines are taut, careful design is needed to pre-tension the lines and prevent them from going slack, when snatch loading can occur and so these moorings are not usually suitable for sites with large tidal ranges [4].

3.2 Catenary mooring

Catenary mooring systems have been a popular choice in the mooring of wave energy devices to accommodate the wide variety of sea states to which the devices are exposed. In its most basic form, the mooring line can be made up of relatively inexpensive components, typically chain and synthetic rope, Figure 3-1 (b), compared to that of other mooring types. However, these moorings can be optimised to give specific properties by altering the material types in different sections of the line. Catenary lines take up a larger area, but their compliance may result in lower peak loads compared to taut moorings.

3.3 S-shape: Catenary with buoy and clump weight

A technique commonly used to reduce the footprint and the damping effects of a mooring system involves introducing floats and clump weights into the line, Figure 3-1 (c). This results in a more complex line and an increased risk of failure owing to the increased number of components. For small horizontal excursions from equilibrium the mooring response is approximately linear, however for large excursions the loading becomes highly non-linear [11].

It has been shown that for an S-shape mooring that has a surface buoy, the size and shape of the buoy will have an impact on the peak line tensions [12] and it will be subject to wind and current loading [4]. Results indicate that with the spectral peak period close to the natural period of the moored device, a configuration with a smaller surface buoy is likely to result in higher peak mooring loads. However, when the incident spectral peak is dissimilar, a smaller buoy results in lower peak mooring tensions. Therefore the size and design of surface buoys need to be designed according to local conditions [12].

Owing to the performance of the OWC being a function of the stiffness, mass and damping characteristics of the body and mooring system, it is important to minimize the vertical restoring forces of the moorings on the device. Results shown in Figure 3-2 demonstrate how a catenary with clump weights and floaters (S-shape) mooring system can reduce the damping effects when compared to a chain or hybrid chain/rope catenary [13]. With lower damping, the movement of the device can be larger and power production higher.

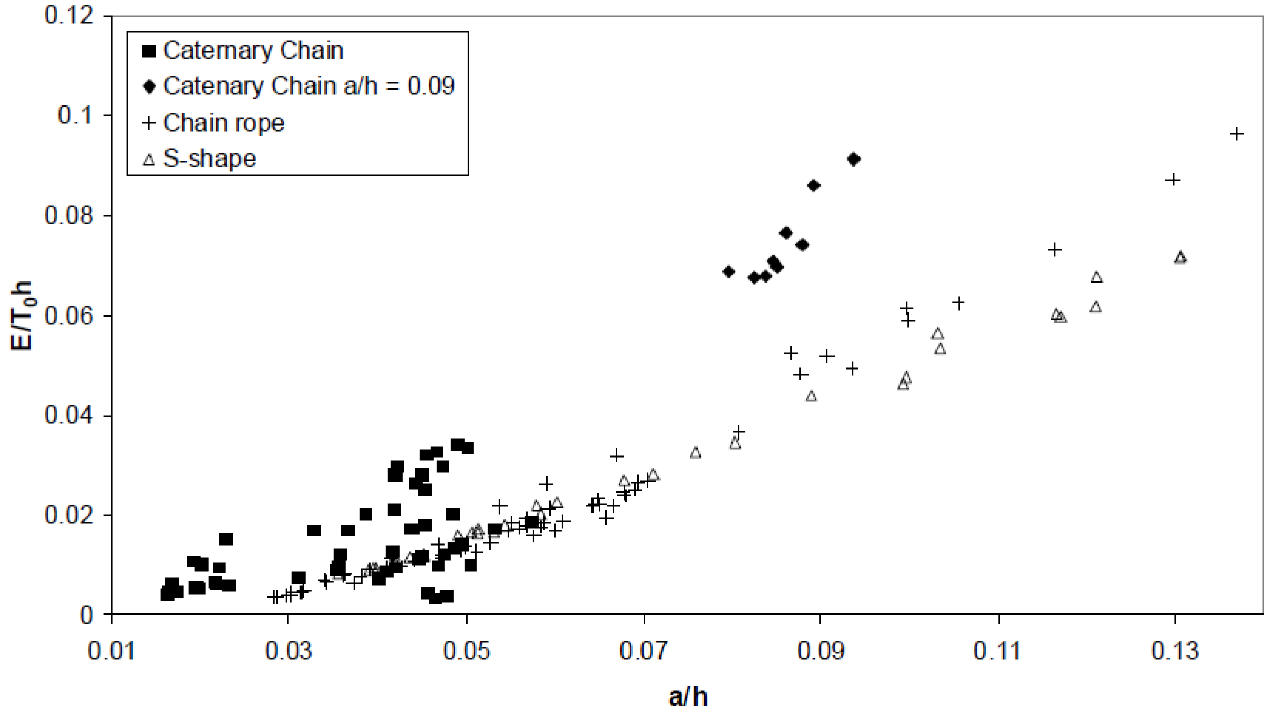


FIGURE 3-2 NON-DIMENSIONAL MOORING DAMPING (E/T_0h) OF THREE MOORING CONFIGURATIONS AS A FUNCTION OF NON-DIMENSIONAL WAVE AMPLITUDE (a/h) [13].

4 Array configurations: initial assessment

In order to define a basis for the selection of array configurations to be tested, a set of assumptions and constraints for the non-rigid array or inter-moored devices are summarised in Table 4-1. The scaling of the devices, the spacing of devices in the array and the scope of the mooring lines (the line length to water depth ratio), are all interrelated constraints. The choice of scale was driven by the need to test an array that offered a similar installed capacity as an offshore wind turbine but that also would fit in the Ocean Basin at Plymouth University.

TABLE 4-1 INITIAL ASSUMPTIONS AND CONSTRAINTS OF THE NON-RIGID ARRAY OF INTER-MOORED DEVICES.

Category	Assumption
Array geometry	Five devices to be used
	Geometry to remain the same between experiments
	Spacing to be no less than 6 *D* (device diameters)
Device	OWC spar buoys to be used
	1:40 scale
	Full scale device: 12 m diameter
Moorings/connections	Able to be individually moored for baseline comparison
	Mooring based on recommendations from IST
	3 point slack moorings to be used for individually moored case
	Scope to be >3
	Inter-device connections must allow access to all devices
	Total number of lines per device ≥3
	Symmetrical arrangement of lines if possible
Anchors	Preference given to gravity anchors over drag anchors
Location	Leixões, Portugal

4.1 Chosen device and individual mooring configuration

OWCs work by powering a turbine, typically on top of the device, driven by the air movement caused by the free surface oscillation. The OWC can be modelled as a second order harmonic system: an oscillating water mass that is subject to a damping force linked to the PTO and a spring or restoring force linked to the free surface motion.

Variations of the OWC spar buoy have already been presented in numerous research papers (see [14] for a review) and the version to be used in the WETFEET project was patented in 2010 [15] with the modification of the bottom section to allow increased mass of the device without changing its hydrodynamic characteristics. The device is presented to some extent in WETFEET D2.1 [16], and will be used as the chosen device to test different flexible array configurations. The key features are highlighted in Figure 4-1, in which *D* represents the diameter of the device.

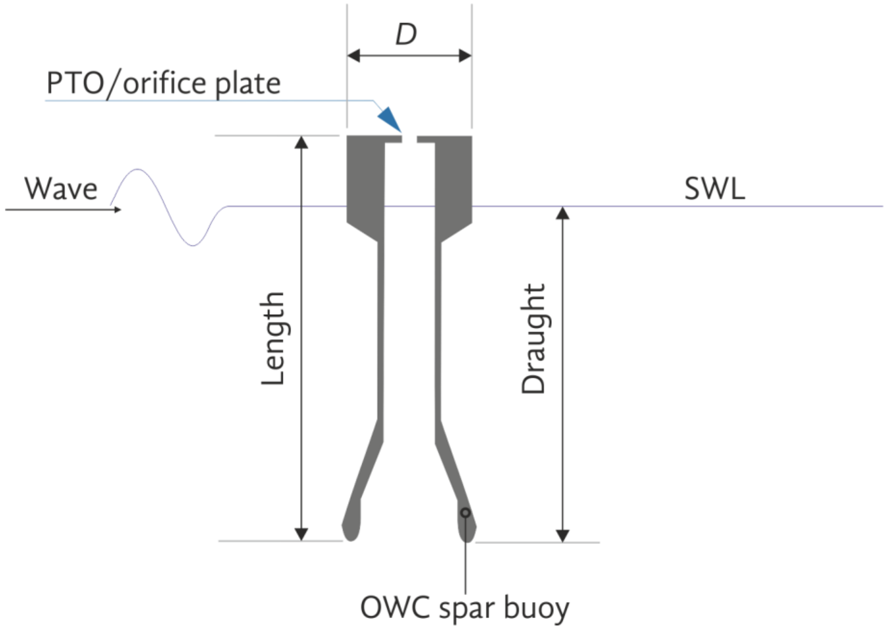


FIGURE 4-1 SKETCH OF THE OWC SPAR BUOY SHOWING THE KEY FEATURES OF THE DESIGN.

The mooring configuration for the individually moored OWC spar buoys is given in Figure 4-2, following the previous tests carried out by IST [14, 17]. The dimensions and the specification of the mooring lines will be reported in D6.5.

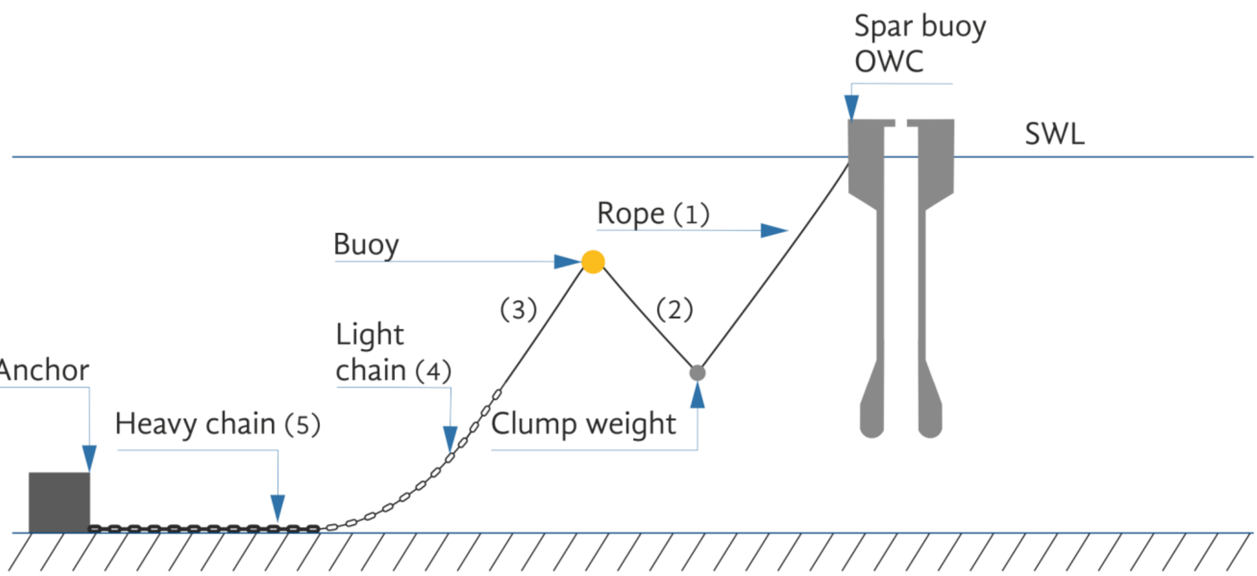


FIGURE 4-2 THE SUGGESTED SEABED MOORING CONFIGURATION.

4.2 Array geometries

This report examines the suitability of three initial array geometries to determine which should be taken through to the physical and numerical modelling stage of the work package. Given the requirement for five devices to be tested, the three initial suggestions are the pentagon, the linear staggered array and the die arrangement, Figure 4-3.

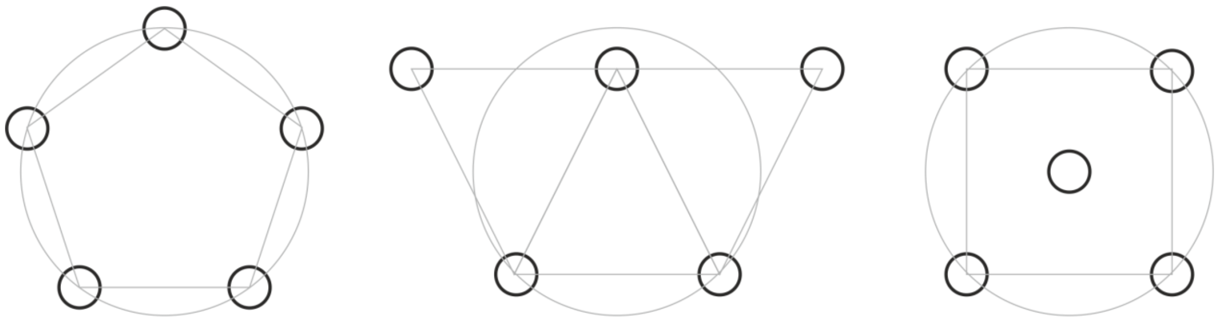


FIGURE 4-3 CONFIGURATIONS OF FIVE DEVICES PROPOSED FOR CONSIDERATION: (A) PENTAGON, (B) LINEAR STAGGERED ARRAY AND (C) DIE ARRANGEMENT. INCIDENT WAVE DIRECTION IS FROM THE TOP OF THE FIGURE.

The linear staggered and die configurations represent examples of the second generation arrays that were discussed in Section 2. The pentagon was proposed because it most closely resembles a circular arrangement, which has been shown to have interesting interaction effects (see Section 5.1 for more details). The final suggestion of the die-like arrangement is compact, offers a high degree of connectivity and is symmetric about two axes and so potentially less dependent on wave direction.

4.3 Interconnection strategies

The way in which the devices are connected together in an array will affect the motion dynamics of the devices. This is why mooring lines should be taken into account at the design stage of any WEC that relies on motion relative to the sea surface as opposed to those that react against fixed structures. As stated in the Introduction, the goal of WP6 is not to suggest an optimum mooring configuration for the OWC spar buoy but to examine the feasibility of the devices sharing mooring components.

The methodology used to assess the configurations will affect the hypotheses that can be tested during the numerical simulation and experimental phase as the parameters that remain the same between experimental sessions will change. For example, the overall objective is to assess the feasibility of shared moorings; array performance is a vital

component of the feasibility score but its optimisation is not the objective. Indeed, a modest performance drop may be mitigated by savings in the capital expenditure (CAPEX), and potentially even the operating expenditure (OPEX), of the array. The aim is to quantify the performance while trying not to modify the dynamics of the array too much. The approach is then to determine a series of interconnections that broadly retain the mooring forces that the devices experience individually.

One methodology is to investigate progressively higher degrees of component sharing, starting with shared anchor points and moving to removal of seabed moorings and replacing them with interconnection lines, shown diagrammatically in Figure 4-4. However, in this approach, whereas the mooring lines can be designed to provide the same static restoring force, the hydrodynamic response of the array may be different for each configuration.

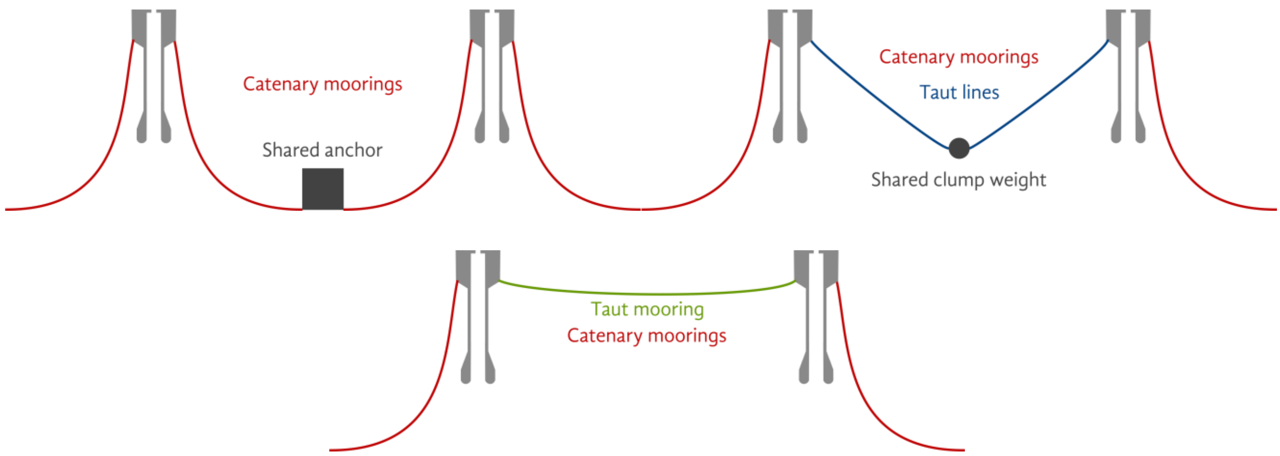


FIGURE 4-4 PROGRESSIVELY INCREASING THE SHARED COMPONENTS BETWEEN DEVICES RETAINS THE LAYOUT OF THE ARRAY BUT MAY CHANGE ITS DYNAMIC RESPONSE.

An alternative strategy is to increase the interconnectivity of the devices while reducing the number of lines attached to the seabed. This strategy examines the hypothesis that the overall cost of seabed moorings and connecting lines can be reduced; it also tests whether the number of seabed mooring lines can be reduced if the array has a greater level of interconnectivity. This strategy allows the trade-off between performance and survivability to be examined. If the connectivity required to ensure a comparable level of survivability were too high, the associated cost would be too great, making the concept of interconnectivity financially unfeasible in this instance.

Figure 4-5 shows the experimental design proposal of a linear staggered array concept (top), the pentagon concept (middle) and the die configuration (bottom) in both the individually

moored configuration and an interconnected state. Three-dimensional views of the configurations are given in the Appendix.

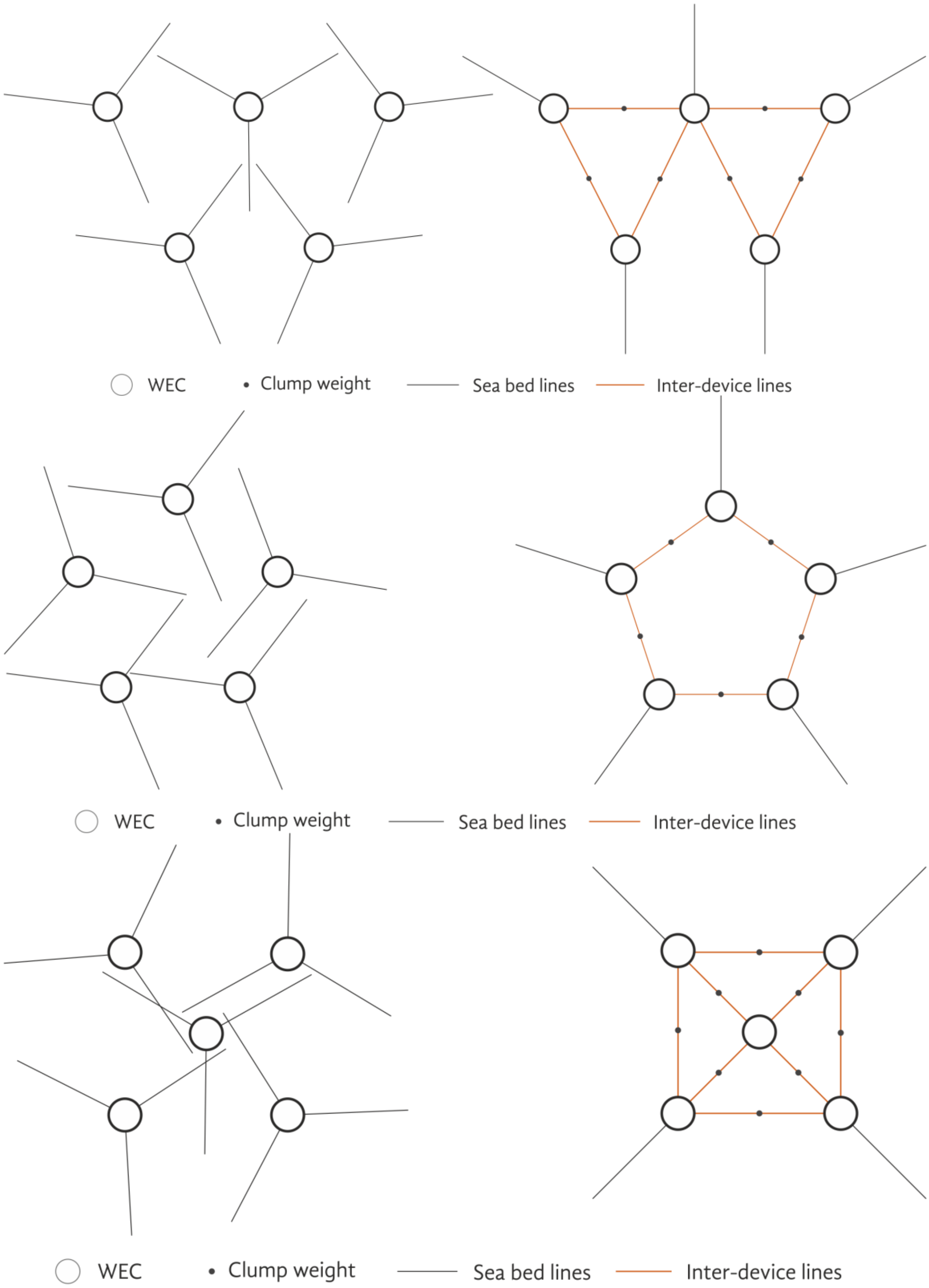


Figure 4-5 The proposed configurations in the individually moored (left) and most interconnected (right) arrangements. From top: linear staggered; pentagon; die. Elements are not shown to scale.

5 Array assessment results and discussion

The assessment of the different configurations comprises many factors, beyond simply power production. The evaluation of the proposed configurations takes into account both qualitative and quantitative aspects relating to the array. The assessment criteria include factors relating to array performance, survivability, cost, environmental impact, space utilisation and electrical connections to the shore. Where possible, quantification of the performance metrics has been suggested.

5.1 Array interference and optimum power production

In an array, constructive or destructive interferences between the devices are due to the radiation/absorption phenomenon. The power production performance of an array of axisymmetric point absorbers depends on the spacing between the devices [9]. Optimising the spacing is fundamental because in theory, all the incident wave power to an array of point absorbers may be absorbed by the array if optimal spacing is achieved [18]. For example, in regular waves, the optimal spacing is often a multiple of the half wavelength.

In irregular wave conditions, it is more difficult to achieve optimal configurations for a broad frequency range because some spacings will cause positive interference for some frequencies but generates negative interference for others and as such it is recommended to avoid interference during the first deployments by keeping devices sufficiently sparse [8]. The interaction between devices with a diameter of 10 m was shown to be significant with spacings of less than 10 device diameters [19], Table 5-1.

TABLE 5-1 INTERACTIONS FOR DEVICES WITH A 10 M DIAMETER BASED ON THE SPACING [19].

Absolute spacing [m]	Normalised spacing [multiples of device diameter]	Interactions
<100 m	<10	Between devices: interactions have to be considered
100 – 500	10 – 50	Interactions depend on the configuration, especially when the waves are not aligned with the array
>500	>50	Interactions are negligible

Much work has been carried out on the subject of the optimization of array configurations with regard to device interaction. For example, when positioned in an array, a group of axisymmetric, non-directional devices may perform in a directional sense and produce different power depending on the incident wave direction. Interference can create disparities in the array, meaning that some devices work at their full capacity whereas others work under their maximal capacity [10].

The effects of device shadowing, which may be significant with the die arrangement, have been highlighted as a key parameter to minimise to improve array power output [20]. Two of the concepts under consideration are the linear staggered arrangement and the pentagon shape (Figure 4-3). A linear staggered array of five devices was shown [20] to produce a higher interaction factor, $\bar{q}$, than a circular or linear arrangement at certain values of non-dimensional wave number, $2ak_o$, Figure 5-1. The interaction factor is defined as the ratio of the total power from the array to that of the same number of devices in isolation 5-1 and so represents the power amplification properties of the array configurations.

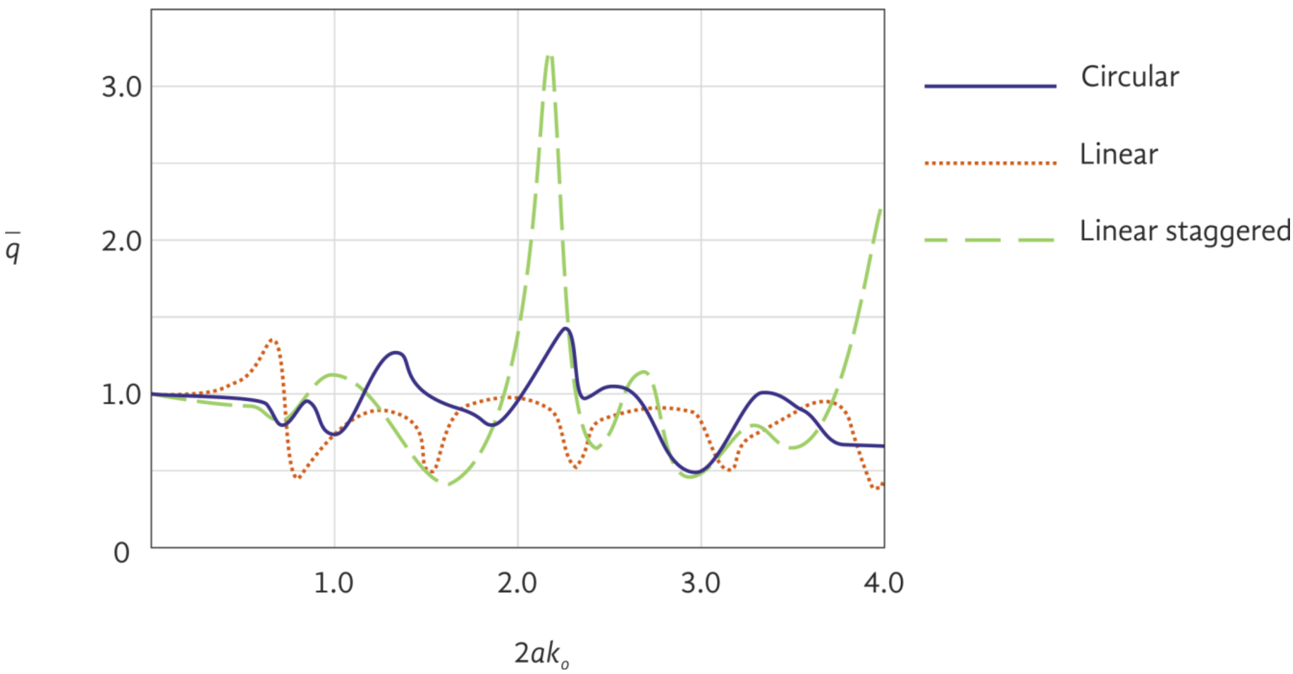


FIGURE 5-1 SPECTRAL INTERACTION FACTOR, $\bar{q}$, OF A CIRCULAR, LINEAR AND LINEAR STAGGERED ARRAY CONFIGURATION WITH REACTIVE TUNING, REDRAWN FROM [20].

$$\bar{q}(k_0,\beta) = \frac{\sum_{J=1}^{N} P_j(k_0,\beta)}{NP_0(k_0,\beta)} \qquad \textbf{5-1}$$

Where:

P_j is the array device power [W]

k_0 is the wave number of the incident wave field [m^{-1}]

N is the number of devices

β is the wave heading angle [rad]

P_0 is the power of an isolated device [W]

It can be seen from Figure 5-1 that when optimized to the local conditions, a linear staggered arrangement can outperform its circular or linear counterpart of equal device number.

The linear staggered array would seem to represent a good choice for the array to be tested as part of the WETFEET project as it suggests that under certain wave conditions, the array will perform better. However, this causes two problems. First, positive array interactions at certain frequencies in an irregular wave spectrum may cause much larger motions and mooring loads. For power production, this is positive outcome but one that might also induce large loads on the mooring lines. It is possible that certain frequencies would need to be avoided during experimentation to keep the mooring loads within the specification of the lines used. In the real world, avoiding specific frequencies would be either impossible or necessitate an elaborate survivability strategy. The second problem is that it would be harder to isolate the effects of the shared connections if there is a pronounced effect relating to the non-dimensional wave number, itself a product of the incident wave number and the spacing between devices.

The pentagon array suggested in Section 4.2 is the closest to the circular array investigated in [20], where it was shown that a circular array had a more consistent array interaction factor across the range of non-dimensional wave number values than the linear staggered configuration, Figure 5-1.

The die array is compact and allows the array to be extended in a modular way. It has a lower order of rotational symmetry than the pentagon array, but a higher degree of reflectional symmetry. In terms of performance, there are expected to be more prominent interactions than with the pentagon arrangement, owing to the greater amount of device shadowing that may occur.

5.2 Survivability

The ocean is a difficult environment in which to operate and because of this costs are often very high. The engineering of a marine device or structure is often a compromise between cost and survivability; components need to be cheap enough to make a project feasible but strong enough to withstand extreme loads. Even when not operating in extreme conditions, hydrodynamic interactions may lead to large mooring loads and large device excursions. The array configurations will be judged on two aspects of survivability. First, using the proposed example site for the full-scale arrays, an environmental loading case will be used to calculate the approximate peak tensions in the mooring lines for each configuration. These results will be compared with those reported in D2.1. Secondly, the array spacing will be considered with

respect to the maximum line extension to examine whether, and under what conditions, device collision is possible.

5.2.1 Example site election and environmental loading

The specific mooring line, chain and anchor costs will be location specific due to the local environmental loading conditions. For this work package, Leixões, Portugal, as described in WETFEET deliverable D2.1 [16] will be used to assess the loading requirements of the mooring systems. If one assumes the 100-year return period wave regime of the Leixões site, the wave variance spectral density, *S*, as a function of wave frequency, ω , Figure 5-2, can be used to estimate the tension in the lines.

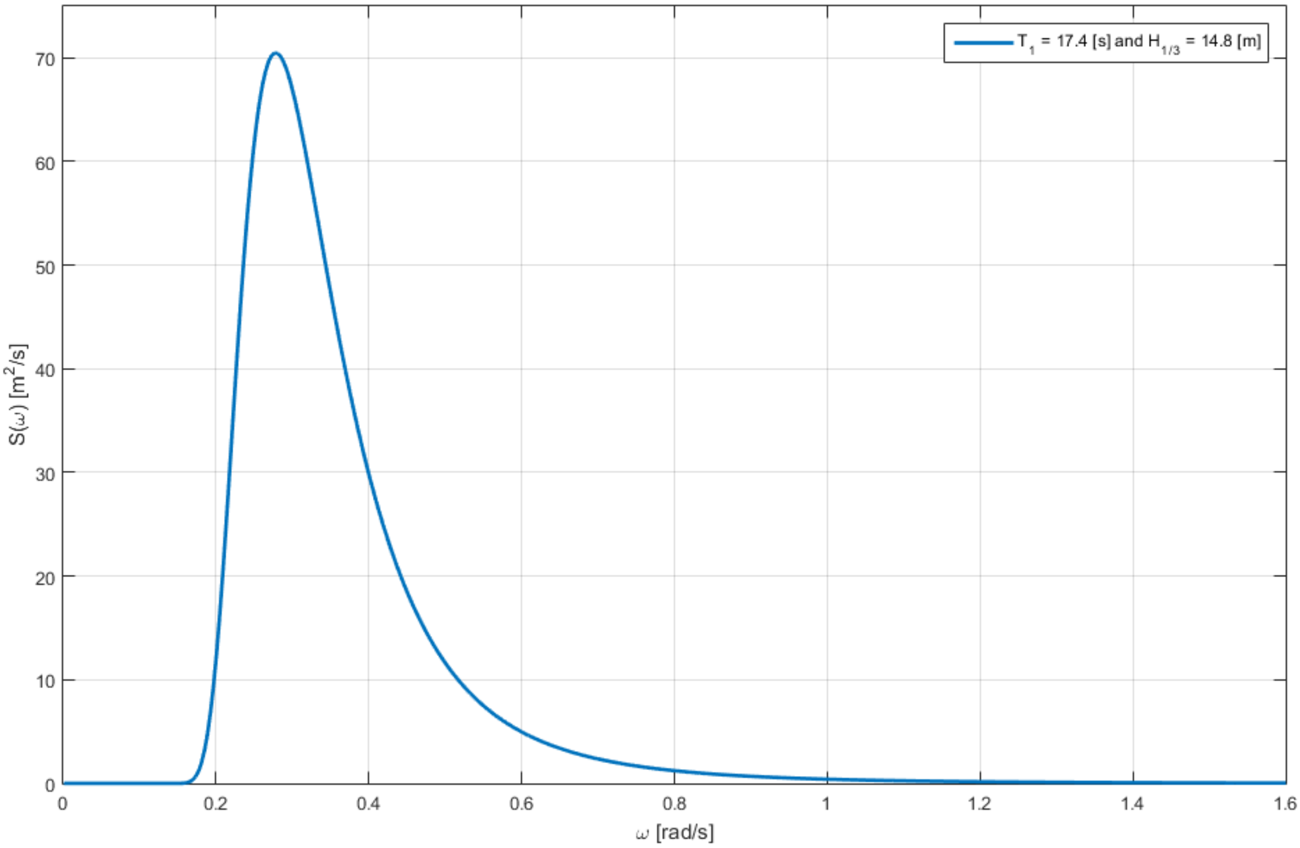


FIGURE 5-2 A PIERSON-MOSKOWITZ SPECTRUM FOR A 100-YEAR RETURN PERIOD FROM LEIXÕES, PORTUGAL.

A local current speed of 0.65 m/s due to the sum of wind and tidal generated current can be assumed from information collated as part of WETFEET D2.1 [16]. The combination of these loads can then be used to assess the configuration options with regard to load sharing of lines. From WETFEET D2.1 [16], the regular design wave for the 100-year return period has a maximum wave height, H_{max}, and associated period, T_{max}, as calculated from Equation 5-2,

with g representing the acceleration due to gravity and H_s representing the significant wave height.

$$H_{max} = 1.86 * H_s \tag{5-2}$$

$$T_{max} = 14.4\sqrt{\frac{H_s}{g}} \tag{5-3}$$

Therefore, using H_s from the Pierson-Moskowitz spectrum in Figure 5-2, the wave induced forces, F, as a static linear approximation can be calculated according to the Morison equation:

$$F = C_m \rho \frac{\pi}{4} D^2 \dot{u} + C_d \frac{1}{2} \rho D u|u| \tag{5-4}$$

Where

C_m is the coefficient of mass

ρ is the fluid density [kg/m^3]

D is the device diameter [m]

$\dot{u}$ is the particle acceleration [m/s^2]

C_d is the coefficient of drag

u is the particle velocity [m/s]

By assuming C_m and C_D are equal to 2 and 1 respectively [21] the wave-induced load on the spar buoy, can be calculated using Equation 5-4. This results in a wave loading of 612 kN combined with a further 42 kN due to the current loading, yielding a total environmental horizontal loading of 654 kN (approximately 67 tonnes). If a factor of safety in accordance with the DNV-OS-C101 standard [22] of 1.7 for a quasi-static calculation is used, a design load of 1.1 MN (112 tonnes) can be derived.

Results from 10 sets of 3-hour OrcaFlex dynamic simulations with the a 1D beam model of the OWC spar buoy [16] indicate that maximum peak tensions at the fairlead are 4.90 MN (499 tonnes) at full scale. As this figure has been calculated considering the dynamics of the system, a factor of safety of 1.3 can be accepted [22], yielding a design load of 6.37 MN (648 tonnes) [16]. This is approximately six times greater than the design load calculated using the static linear approximation; the more conservative value will be used to estimate line tensions.

5.2.2 Device spacing and collision avoidance

Risk and redundancy for the purpose of this report is considered as the ability of each configuration to avoid device collision in the event of a line failure or in the situation of a fully taut mooring line (fail safety). As summarized in WETFEET D2.1 an upgraded version of the

mooring system used in the MARINET Plymouth University array testing [23] is required to provide additional horizontal restoring forces [16]. The new mooring line consists of three synthetic fibre and two chain sections as shown by Figure 5-3 with full-scale properties described in Table 5-2.

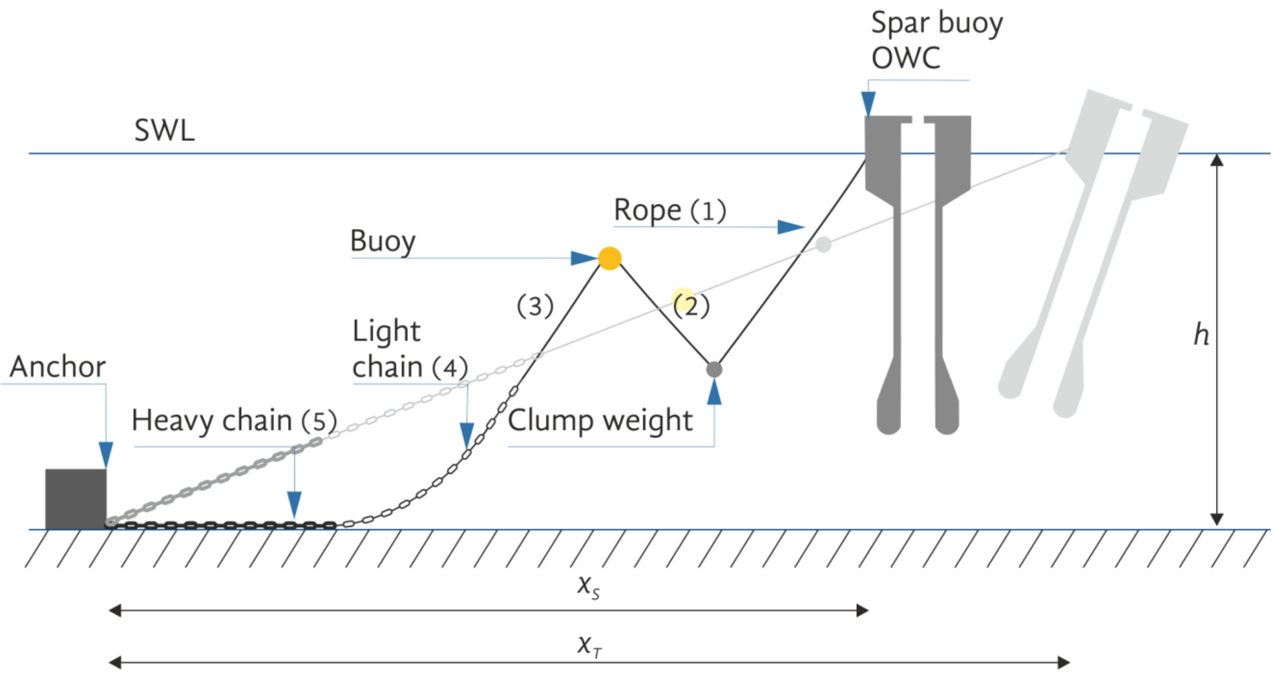


FIGURE 5-3 THE UPDATED SEABED MOORING SYSTEM IN A FULLY LIFTED SCENARIO.

The properties defined in WETFEET deliverable D2.1 and given in Table 5-2 are used throughout this deliverable to quantify the survivability, cost reduction and other related aspects.

Table 5-2 Mooring system properties as defined in WETFEET D2.1.

Mooring properties	OWC Spar buoy 3x9	OWC Spar buoy 6x18	OWC Spar buoy 12x36
Horizontal length [m]		195.2	
Water depth [m]		60	
Weight dry mass [kg]	2562	10622	63252
Weight density [kg/m^3]		5600	
Buoy dry mass [kg]		100	
Buoy density [kg/m^3]		250	
Length of line (1) [m]		142.45	
Length of line (2) [m]		42.45	
Length of line (3) [m]		46.65	
Length of light chain (4) [m]		32	
Light chain diameter [mm]		20	
Light chain weight per unit length [N/m]		75	
Length of heavy chain (5) [m]		50	
Heavy chain diameter [mm]		60	
Heavy chain weight per unit length [N/m]		675	
Surge resonance period [s]	90	142	146

As stipulated in Table 5-2, the projected horizontal length of the upgraded mooring is x_S = 195.2 m. Therefore the fully taut situation during maximum environmental loading can be calculated as follows:

$$x_T = \sqrt{(L_1 + L_2 + L_3 + L_{LC} + L_{HC})^2 - h^2} \qquad \textbf{5-5}$$

Where h is the water depth, subscripts 1 to 3 represent the synthetic line sections shown in Figure 5-3 and subscripts LC and HC represent the light and heavy chain sections respectively. Equation 5-5 yields a fully taut horizontal length x_T = 308 m, resulting in a difference of Δx = 112.8 m in an extreme storm condition.

The extension of the inter-device connections can be limited by reducing the line length between devices and by increasing the point mass to match the environmental loading. Therefore it is necessary only to assess the array spacing with respect to the seabed mooring line extension, Δx. To ensure collision between devices is not possible, the array spacing needs to be sufficiently large to prevent contact in the unlikely event of two opposing seabed line taut situations. The minimum non-dimensional array spacing required of the proposed seabed mooring line in order to avoid any collision in a fully lifted situation is:

$$\begin{gathered} A = 2 * \Delta x \sin(60) \\ 195.4 = 2 * 112.8 \sin(60) \\ 195.4 = 16.3\, D \end{gathered} \qquad \textbf{5-6}$$

where D is the device diameter and A is the spacing between the devices, as shown in Figure 5-4. These values do not take into account any pitching of the device and so are slight underestimates and they rely on the assumed angles of the mooring lines given in Figure 5-4. A similar approach is followed for both the pentagon and the die configurations, with maximum spacings summarised in Table 5-3.

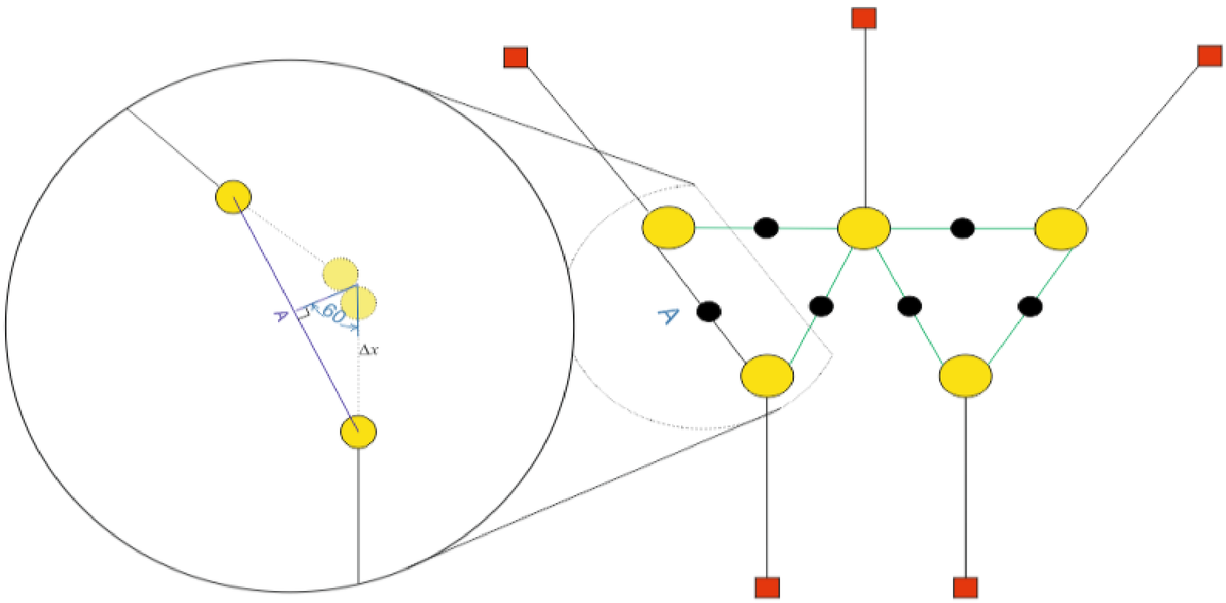


FIGURE 5-4 THE ARRAY SPACING REQUIRED TO ENSURE CONTACT BETWEEN THE DEVICES IS NOT MADE WHEN THE SEABED LINES ARE FULLY LIFTED.

The situation of two fully taut lines is highly unlikely but it permits a quantification of survivability. If instead the limiting factor is taken as no collisions with only one line fully taut, then the device minimum device spacing is halved. From this the maximum spacing between devices that can be accommodated in the basin can be calculated, Table 6-2. This maximum spacing guarantees that collision between devices will not occur with one line fully taut, even with some movement from the other device's bed line. This maximum spacing guarantees that collision between devices will not occur with one line fully taut, even with some movement from the other device's bed line.

TABLE 5-3 ESTIMATE OF THE MAXIMUM DEVICE SPACING NECESSARY TO AVOID COLLISIONS.

Configuration	Two taut lines	One taut line
Pentagon	13.30 D	6.65 D
Linear staggered	16.30 D	8.15 D
Die	18.80 D	9.40 D

These values represent a simple method to estimate collision avoidance spacing based on the geometry of the array configurations presented. More sophisticated methods have been developed [24] that taken into account the cyclic wave loading as well as a static load and these methods will be considered throughout the rest of the Work Package.

5.2.3 Line tension and redundancy

A static equilibrium methodology can be adopted to assess an approximation of the line tensions in each concept in the comparable configuration of each device having three points of contact. The worst case scenario consists of each device loaded with L_E = 6.37 MN (*q.v.* Section 5.2.1) with no load being translated to other devices or lines, as shown in Figure 5-5. Line numbering for the other layouts is given in the Appendix.

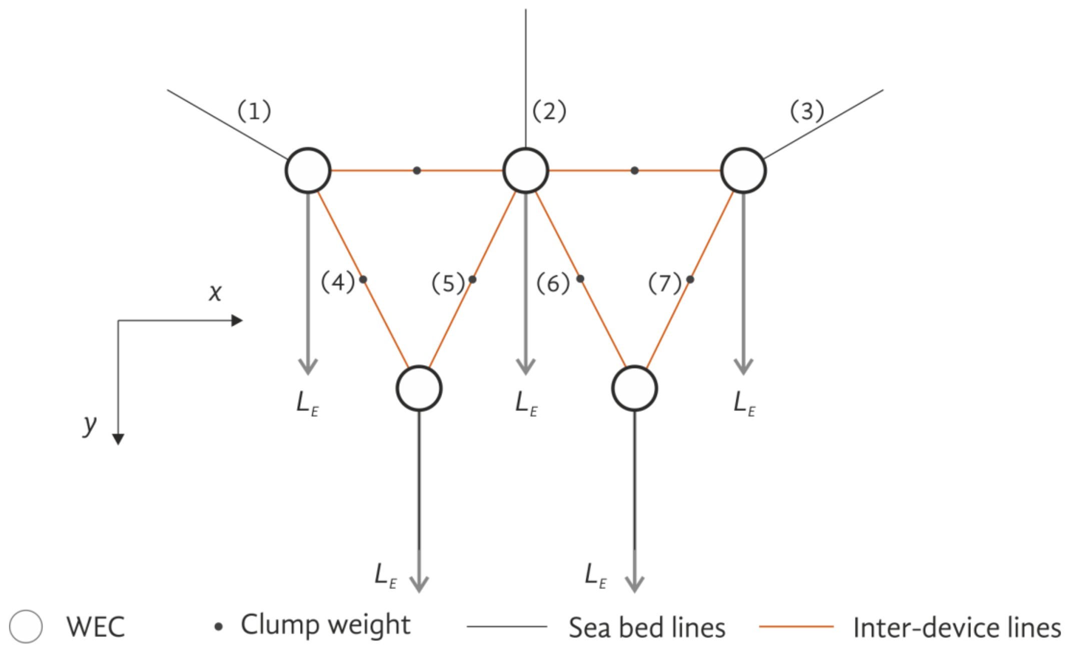


FIGURE 5-5 FREE BODY DIAGRAM FOR THE LINEAR STAGGERED ARRAY WITH EACH DEVICE SUBJECT TO THE FULL ENVIRONMENTAL LOADING.

The tension, T, in the lines, as numbered in Figure 5-5, can then be estimated using statics:

$$\sum F_x = 0 = T_5 \sin(30) - T_4 \sin(30)$$

$$\therefore T_5 = T_4$$

$$\sum F_y = 0 = T_5 \cos(30) + T_4 \cos(30) - 6.36$$

$$\therefore 2T_5 \cos(30) = 6.36$$

$$\boldsymbol{T_5 = T_4 = \frac{6.36}{2\cos(30)} = 3.67\ \mathrm{MN}}$$

The calculated tensions in each line can be seen in Table 5-4; these are the peak static tensions since loading the array would cause the devices to move, the line angles to change and the load to be shared among more lines. It can be seen that due to the lack of load sharing in the pentagon concept, the average resultant line tension is generally much higher than for the other configurations. However, the largest values are seen with the linear staggered array, which also shows the largest range of values between lines. It can intuitively be seen that if the environmental loading applied at 90 degrees, the sum of the tensions in the lines of the pentagon array will remain approximately unchanged, whereas those of the linear staggered array will be significantly higher.

TABLE 5-4 ESTIMATES OF THE STATIC LINE TENSIONS IN THE PROPOSED CONFIGURATIONS, WITH THE HIGHEST TENSION IN FOR EACH CONFIGURATION IN BOLD.

Line number	Pentagon line tension [MN]	Linear staggered line tension [MN]	Die line tension [MN]
1	6.36	**12.72**	**8.99**
2	**9.33**	6.36	3.18
3	**9.33**	**12.72**	3.18
4	7.34	3.67	6.36
5	7.34	3.67	0
6	0	3.67	0
7	-	3.67	-

Experimentation with a linear staggered configuration of five individually moored OWCs has also been carried out to investigate extreme mooring loads within arrays [25]. Findings of the experiment suggested that peak loads on mooring lines of a multi-WEC array may be considerably higher than a singular device. Figure 5-6 shows results from [26] that describe the probability of the mooring loads exceeding a certain value. It can be seen that the more devices in an array, the larger the potential peak loading value, although loading of a certain value may be less probable.

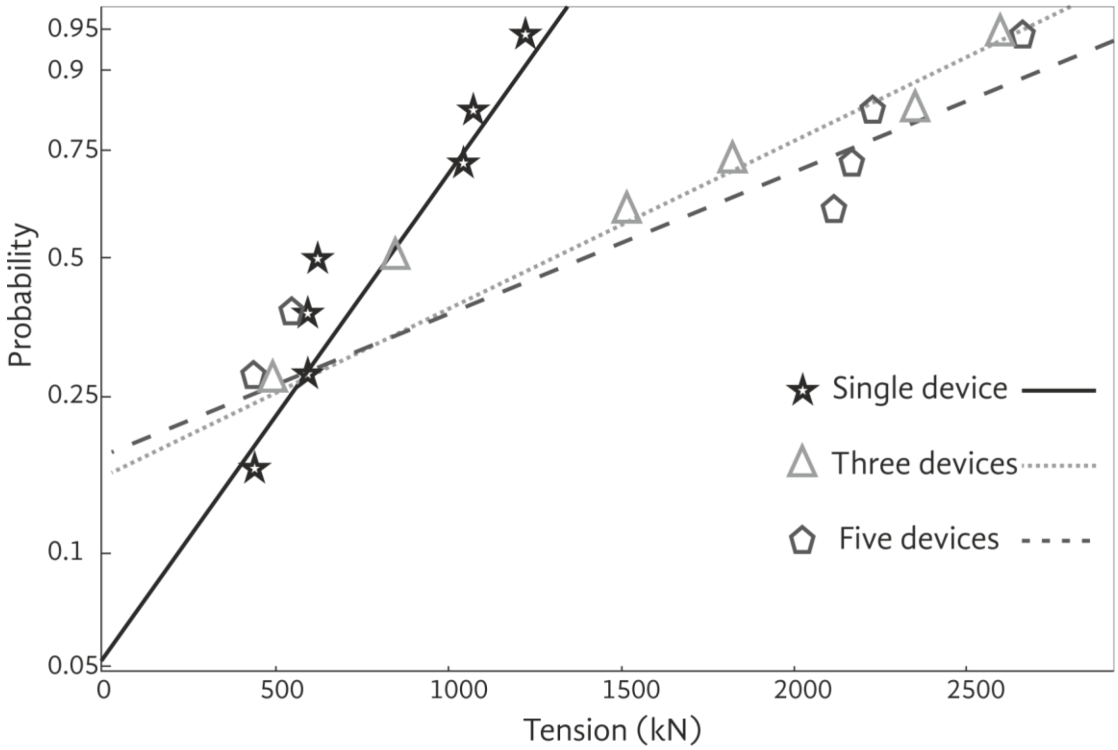


FIGURE 5-6 PROBABILITY OF PEAK MOORING LINE TENSION EXCEEDANCE FOR SINGLE OWC DEVICES AND ARRAYS OF THREE AND FIVE OWC DEVICES, REDRAWN FROM [26]. LINEAR FIT LINES ARE ALSO SHOWN.

Until the mooring configuration has been properly defined and the loads have been quantified, analysis on the rupture of mooring lines will be simplistic. At this stage, the number of broken lines that would result in a possible collision was used to define the line redundancy. Due to the nature of component sharing and removing seabed lines, all three layouts have a line redundancy score of 1. When designing the mooring, care must be taken to have a high enough safety factor in the mooring lines such that the rupture of one line does not cause the remaining lines to surpass their design loads. This would cause successive failures of the mooring lines and of the whole array.

5.3 Cost reduction

The costs associated with the different configurations are perhaps the most difficult parameters to quantify at this early stage of the study, as there are a number of factors to be included and assumptions that need to be made. Estimates of the component costs of the mooring lines, anchors and interconnection lines are calculated for each configuration at full scale. This includes clump weights and buoys but not connection links, shackles etc. Fuel and crew costs for the installation process will not form part of the selection but, where possible, approximate costs have been noted. Operation and maintenance costs will not be considered, but as part of the WETFEET project, WP3 will consider breakthroughs relating to O&M and WP7 will consider aspects of cost including those related to O&M.

In order to associate a cost to each concept, values from Table 5-5 will be used. These values will be variable according to economies of scale, future technological advances and project specifics, but values are accurate as of March 2016 to be considered as a good approximation. The costs will be further refined in the future project reports (in particular those resulting from WP7) once the numerical and physical modelling investigations undertaken here have been carried out and more accurate data on line loads are available.

TABLE 5-5 SUMMARY OF MATERIAL COSTS FOR A GENERIC MOORING SYSTEM.

Component	Cost
Gravity clump anchor [EUR/t] (1,2)	576
Steel gravity anchor casing (fabricated) (3) [EUR/t]	5120
Submerged buoyancy, 1000 mm diameter, 280 kg buoyancy (4) [each]	4288
Clump weight, concrete (2) [EUR/t]	576
Generic drag anchor (5) [EUR/t]	3200

(1) Source costs given in GBP and converted to EUR.
(2) Adamcrete
(3) Seatricity
(4) Trelleborg
(5) Sotra Anchor & Chain

The costs are estimated based on the assumption that the test site conditions are heterogeneous across the full array area, so that all anchors, weights, buoys and lines providing the same function will be identical regardless of their place in the array.

5.3.1 Chain

The chain costs will be a function of array spacing. If the interlinking of devices is to be financially beneficial the array spacing needs to be suitably small to ensure the cost of the inter-device lines and clump weights amount to less cost than individually mooring the devices.

Figure 5-7, originally published in EquiMar D7.3.2 [11] shows an example of mooring line costs per unit length. As the proposed mooring lines are composed of varying materials the total cost will be a combination of values. Figure 5-7 shows that the cost for the required seabed mooring lines (labelled R3, R3S and R4) start at approximately £130/m (EUR 167/m) for a line with a breaking load of around 648 tonnes.

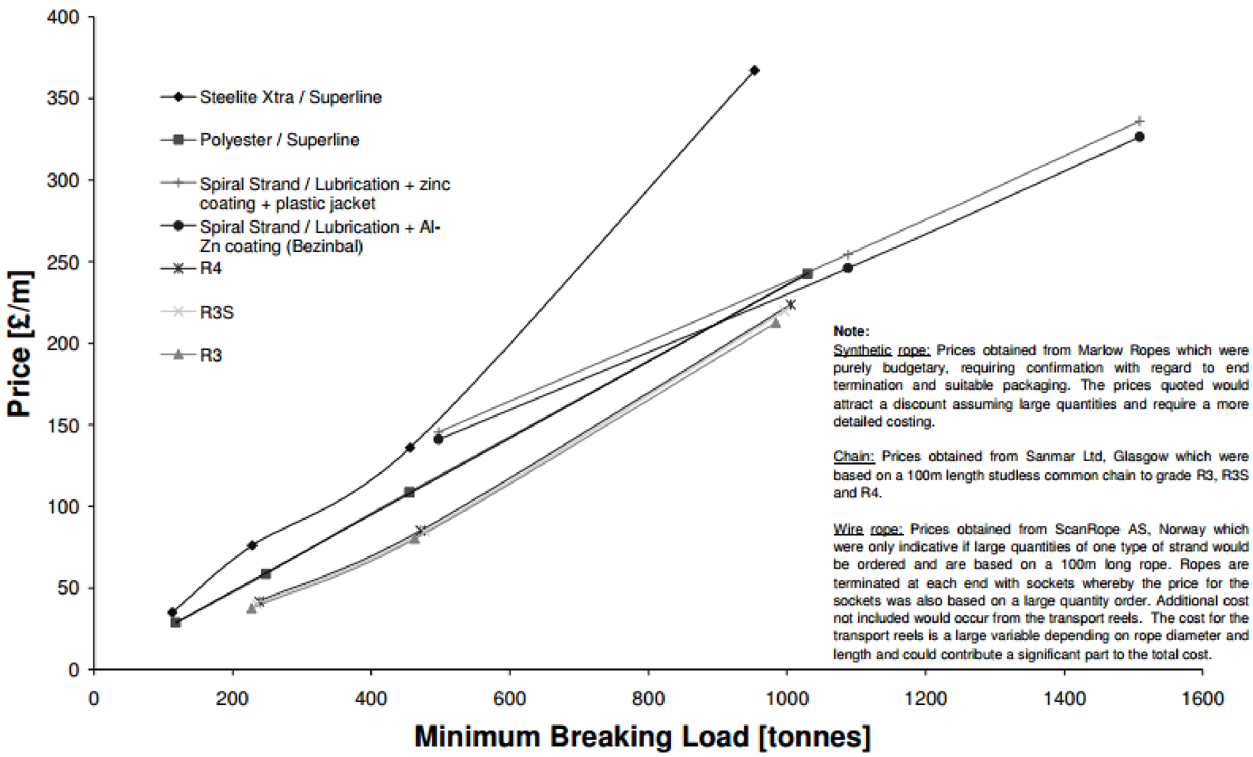


Figure 5-7 Mooring line material costs per unit length as a function of minimum breaking load collated from various sources [11].

5.3.2 Anchors

Anchor costs will depend upon the array and mooring design. If a catenary mooring is to be employed, the anchoring system must provide an equal and opposite restoring force to the environmental loading and lifted chain length. For catenary moorings, a drag anchor or a gravity anchor will be suitable due to the lack of vertical loading. The holding capacity of the anchor type is dependent on the seabed material and the direction of loading. Figure 5-8 indicates the required mass of a drag anchor suitable for the array mooring system if the seabed is formed of a cohesionless material such as sand,. For example, it can be estimated from Figure 5-8 that a stockless anchor of mass circa 30 kips (13.61 tonnes) would be required to provide a suitable restoring force.

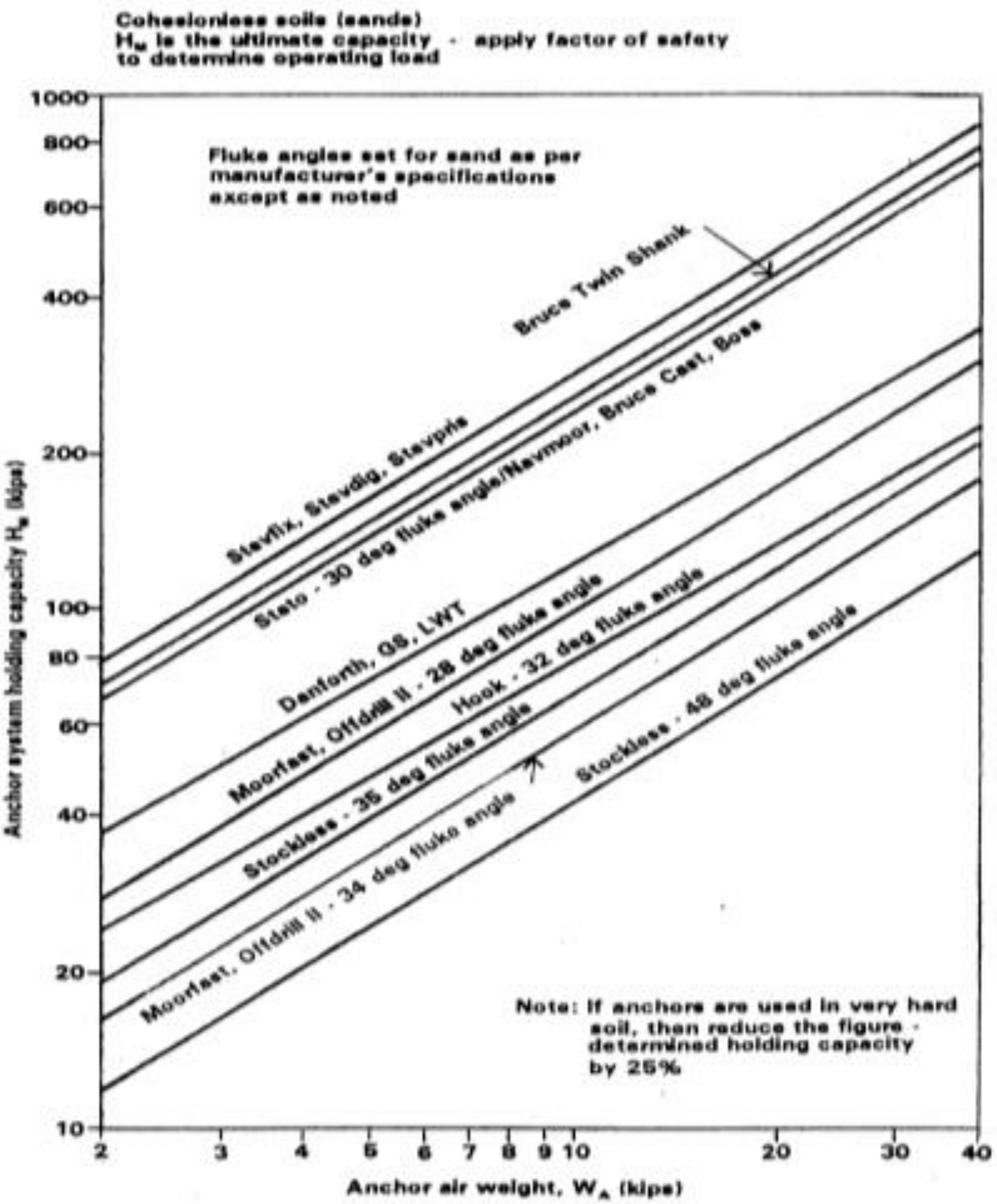


FIGURE 5-8 ANCHOR SYSTEM HOLDING CAPACITY FOR VARIOUS DRAG ANCHOR TYPES IN SAND [27].

Cost data from Table 5-5 can be used to approximate a drag anchor cost of EUR 43k each. If, however, a gravity clump weight anchor is required due to seabed type, the anchor costs could be around EUR 125k (considering a steel fabricated frame with a mass 12% of the anchor).

5.3.3 Clump weight

For the given environmental loading a specific clump weight mass will be required at the cost covered in Table 5-5. Until the dynamic mooring line tensions are known, the cost of the clump weights will be assumed to increase linearly with the number of devices in concept array. In reality, a change in the maximum tension in the line will require a different sized clump weight to be used and the cost will alter.

5.3.4 Spring buoys

Similar to the clump weight costing, mooring line floater costs will also increase linearly with the number of devices in the array. Cost approximations from Table 5-5 can be used to estimate a full scale float cost. If the dry mass of the float is 100 kg and a density of 250 kg/m^3, the volume must be 0.4 m^3, providing a buoyant force of 4 kN. Table 5-5 shows that a float providing 280 kg buoyancy (2.7 kN) costs approximately EUR 4,288. The full scale mooring would therefore require two buoys costing approximately EUR 8,576 or one buoy costing EUR 6,353 if the costs are assumed linear.

5.3.5 Installation and deployment

Since the price of installation vessels is highly variable and relies on multiple factors, the installation costs here are simplified to allow discrimination between array configurations rather than to give an accurate prediction of costs. A full costing report will be one of the deliverables of WP7.

Table 5-6 gives a summary of the offshore vessels that are typically used in marine operations; however, the installation procedures and costs of a WEC array will be unique to each project. The figures in Table 5-6 are conservative estimates based on the literature and do not account for availability, season or crew costs, which themselves may reach USD 60k (EUR 53k) for a deployment lasting a couple of days [28]. Not only are the costs of the vessels highly variable, the choice of vessel will depend on the availability, location, weather, distance to port, sea conditions, tidal ranges as well as the components to be installed [29].

Table 5-6 Deployment vessels needed for a marine operation, their approximate costs and availability [28, 30]. Costs in source material were given in USD and converted here to EUR at a rate of 0.87.

Vessel type	Jobs	Number worldwide	Cost (new) [EUR M]	Specified by	Modern vessels	Example day rate [EUR k]
Anchor handling towing supply AHTS	Towing rigs from one location to another, lift and position rig anchors some drilling	1562 and 120 new	17 – 35	hp	>10000 bhp Winch strength >250 t Anchors to 600 m depth	35 – 57
Offshore supply vessels OSV	Deliver supplies to drilling rigs	1014 and 84 new	13 –26	Cargo carrying capacity or boat length	2 – 4000 dwt deck cargo GPS station keeping ≤12000 hp	8.8
Crew boats	Personnel transfer	500	2.2 – 5.7	Cruising speed		1.8 – 4.2
Offshore tugs	Towing and some anchor handling	-	-	hp	2000 – 9000 hp	4.8 plus fuel (2.3 @ 8 kts)
Barges	Transporting large or heavy equipment	-	-	Cargo carrying capacity or boat length	15000+ dwt (metric)	1.3 – 1.8
Floating cranes	Heavy lifting, pipe lay, pile driving	-	-	Lift load	180 t (angle dependent)	-

Examples of baseline installation costs are typically given per installed capacity (USD/kW or EUR/kW). For example, the baseline installation costs for a wind farm were estimated to be USD 633M (EUR 557M) for a 500 MW installation [31]. If these costs were directly scaled to the five devices in the chosen array, an approximate installation figure for five full-scale devices would be EUR 28M. This is likely to be an overestimate since the vessels needed to install a 5 MW wind turbine, as in [31] are likely to be bigger than those needed to install a full-scale OWC spar buoy, operating in the hundreds of kilowatts range, although this project may have benefitted from 'economies of scale'.

The LCOE calculator developed by the Carbon Trust [29] gives an installation cost per WEC device of between GBP 9.6M (EUR 12.3M) and GBP 11.1M (EUR 14.2M), giving total array installation costs of between EUR 61.4M and EUR 71.0M. These figures are high compared to the cost of a 500 MW installed capacity wind farm (100 device), for which the per device costs were USD 6.3M (EUR 5.5M) [31]. This may be because offshore wind installations are cheaper than WEC installations owing to the maturity of the technology. Another cause for this disparity may be due the economies of scale: that as array/farm sizes increase, the cost per unit will fall.

If a complexity coefficient were applied to the different configurations based on the number of mooring lines and anchors to be deployed, the costs per configuration could be re-estimated, Table 5-7, to allow discrimination between the configurations. This is, of course a simplistic analysis of the relative costs of each of the configurations, however, the range of values calculated in Table 5-7 is less than that given in the Carbon Trust LCOE calculator [29] with optimistic/pessimistic forecasts.

TABLE 5-7 INSTALLATION COSTS RE-ESTIMATED BASED ON THE COMPLEXITY OF EACH CONFIGURATION.

Configuration	Fixed installation costs (1) [EUR k]	Mooring costs (2) [EUR k]	Complexity factor (3)	Total cost for 5 devices [EUR M]
Linear staggered	9677	3584	0.50	57.3
Pentagon			0.45	56.5
Die			0.55	58.2

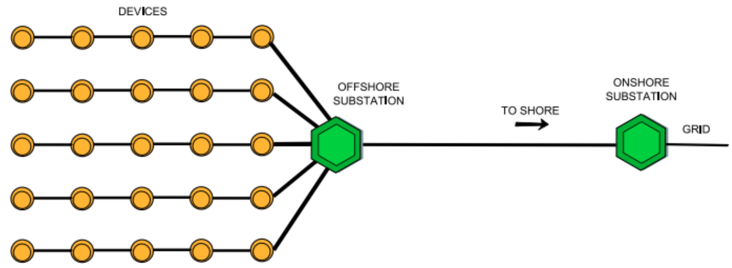
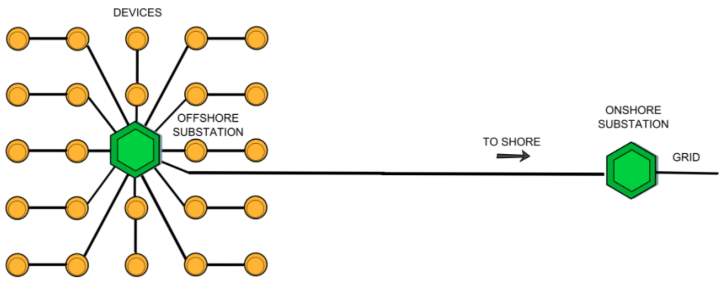
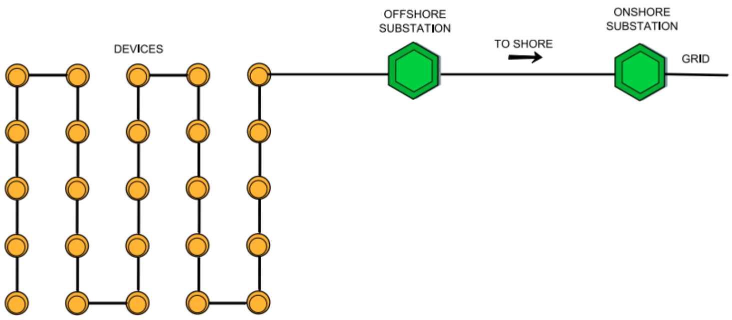
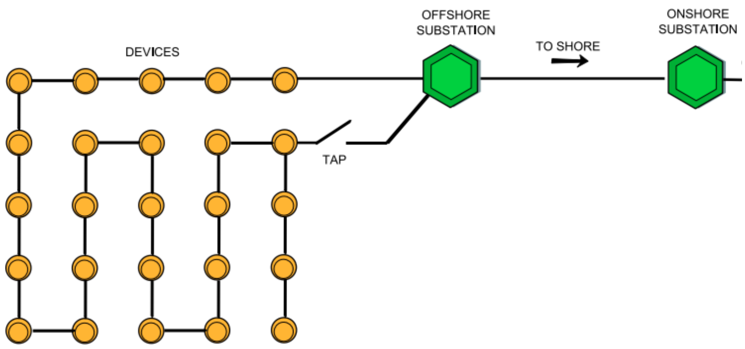
(6) Installation surveys, installation of structure, installation of grid connection, base levels [29]. Source material cost given in GBP and converted to EUR at a rate of 1.28
(7) Base levels [29]
(8) Number of mooring lines, clump weights and anchors divided by sum of average values, data from Table 7-1

5.3.6 Electrical cable costs

Devices producing electricity may be connected to the grid if they meet the required certifications and codes. Ignoring policy, devices could be connected directly to the grid

without need for additional components if a suitable power converter were on board [32]. The alternative is to have a submarine hub where electricity generated by one or more devices is transmitted on-shore, as in the case of Wave Hub. Examples of electrical connections for different positions of offshore substation, depending on the device configuration are given in Table 5-8.

TABLE 5-8 POSSIBLE ELECTRICAL CONNECTION LAYOUTS BETWEEN THE DEVICES OF AN ARRAY [8, 33].

Cluster	Notes
	String Cluster Layout Series of device strings are connected to an offshore substation in parallel. Very popular in wind farms If one string fails, the system continues to produce power.
	Star Clustering Fewer devices on each arm of the substation Popular in offshore wind As only two devices per arm the risk power loss due to failure is reduced compared to the string configuration.
	String with no redundancy Only one transmission cable Minimal cable costs, but any failure results in total power outage.
	String with redundancy Devices are connected along a single cable to reduce cable costs Redundancy cable to form a loop in order to maximize power output in the event of a cable failure.

Distances between devices should be chosen to avoid extreme mechanical loads on power cables or excessive power loss in the cable and extra components can be added to the

electrical cable set-up to mitigate the effects of sideways loading and bending, reviewed as part of the DTOcean project [32]. However, for the purposes of informing the selection of the proposed configurations, for which *a priori* knowledge of such a complex system is not available, the impact of the cabling will essentially follow that of the mooring lines. This means that the cabling may have an effect on the ideal spacing of the devices but that these effects are not quantifiable at this stage of the project.

As explained in Section 5.2, a balance between cable cost and system redundancy needs to be found. To estimate an initial cable architecture cost, each device is considered to be directly connected to a cluster substation, Figure 5-9, as this gives the greatest cable redundancy. The reality of this assumption would become apparent when the cable characteristic constraints, such as maximum loads/bend radii/fatigue properties and component requirements, are known.

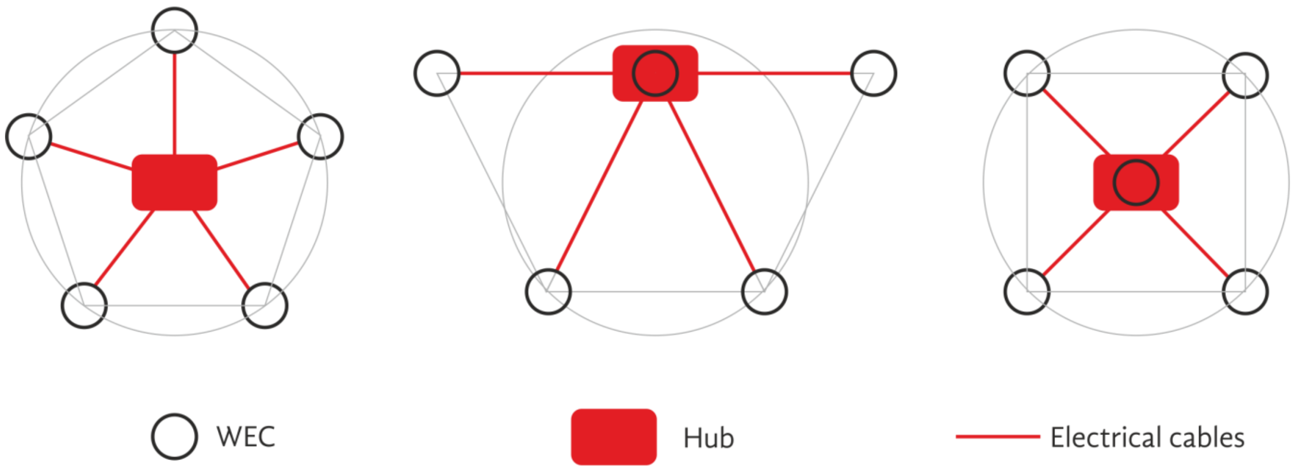


FIGURE 5-9 ELECTRICAL ARCHITECTURE CONSIDERED FOR THE COST ANALYSIS OF EACH CONCEPT.

If one assumes, similar to that of UK offshore and onshore wind arrays, that the electrical interconnectivity between devices is 33 kV (medium voltage) a cost analysis can be approximated from cable costs at WaveHub, Cornwall. Here the 25 km 33 kV cable cost is approximately EUR 10.2M, resulting in a cost per unit length of approximately EUR 410/m [34]. The length of the cables required is a function of the array spacing and is considered to be the sum of the depth and array spacing multiplied by the number of cables required as shown in Figure 5-10.

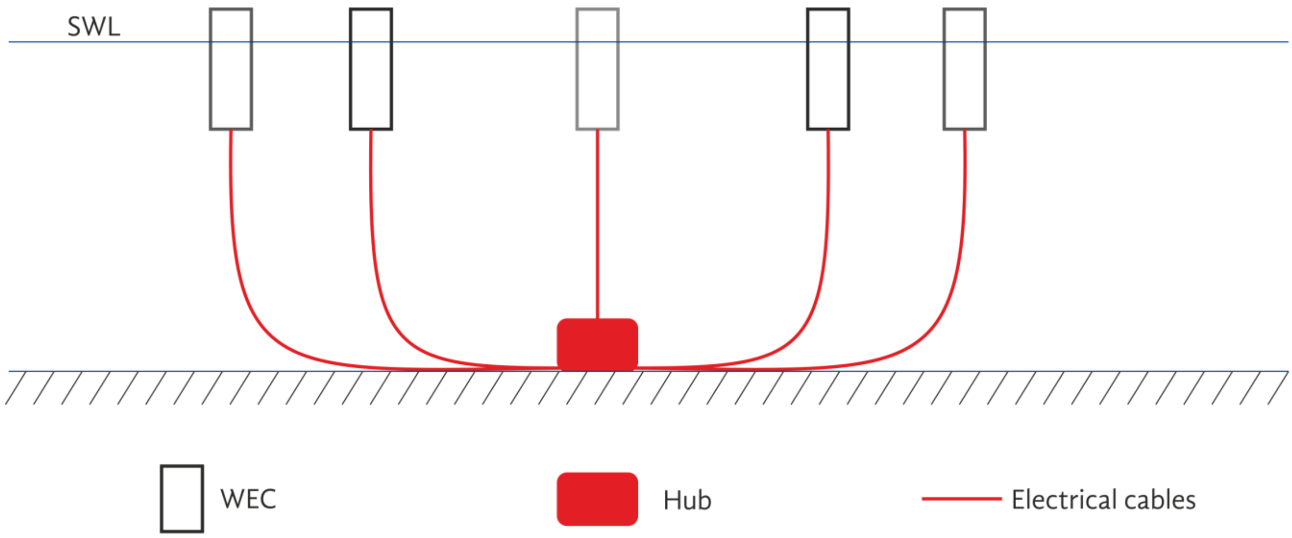


FIGURE 5-10 DIAGRAM INDICATING CABLE LENGTHS REQUIRED FOR PENTAGON CONFIGURATION.

As shown in Table 5-9, the preliminary cost analysis highlights the linear staggered concept as the most cost effective choice owing to the lower array spacing. In reality a full scale wave energy farm of devices will require a full cost analysis and optimization of cabling options with respect to voltage levels, current type (AC/DC), sub stations, rectification and transformation costs. These variables will fluctuate with time and location of the array proposal.

TABLE 5-9 ESTIMATED ELECTRICAL CABLE COSTS FOR EACH CONFIGURATION WITH A 33 KV CABLE.

	Pentagon	Linear staggered	Die
Spacing (1) [*D*]	6.65	8.25	9.4
Spacing distance [m]	79.8	99.0	112.8
Cable length required [m]	699	696	751
Cost of export cable to substation [EUR k]	287	285	308

(1) Based on one taut line collision protection, Table 5-3

5.4 Environmental impacts

The process to obtain consent to deploy structures or objects in the sea includes the requirement to conduct an environmental impact assessment (EIA) since there are many unknowns associated with their potential effects [35]. Within the WETFEET project, a final EIA for large-scale deployment will be included, within the scope of WP7, at a later stage of the project.

Above and beyond the risks presented by a typical WEC array deployed in the sea, the array configurations to be tested here pose additional threats and opportunities to the local environment owing to the sharing of components.

Entanglement in cabling and powerline is an unknown (unquantified) risk [36] for marine mammals but fewer cables in the water should mean a lower risk of entanglement. In addition, smaller, flexible structures such as electrical cables and mooring chains will potentially inflict less damage to marine species than fixed structures in the water column should an impact occur, however, their reduced size provides different cues to marine life on how to avoid them [36]. For this reason, configurations with fewer seabed lines, such as the die configuration, may be preferred.

During installation (and potentially operation), there are potential effects to consider on the benthos (bottom dwelling plants and animals). The most likely impacts during the construction phase are habitat disturbance, increased suspended sediment, sediment deposition, scour and abrasion and release of contaminants from dredged sediments, although seabed disturbance from construction is considered to be local and temporary on par with naturally occurring events [35]. The mooring configuration suggested by IST for the OWC spar buoy (see Figure 4-2 on page 21) may be used with gravity anchors in place of drag anchors, and so represents a less intrusive mooring configuration. The choice of array configuration will have little impact on the effects of the construction phase; however, with shared components meaning fewer anchors and chains in contact with the seabed, there will be less damage to the benthos.

The potential impacts of an array are not just limited to the immediate area, leading to the EU-funded SOWFIA project to report that "zones of influence" be used to classify anthropogenic noise [35, citing, 37]. Underwater noise is of particular concern as it comes under the Marine Strategy Framework Directive (2008/56/EC), which lists the introduction of energy, including underwater noise, as one of the eleven descriptors to be used by EU Member States for determining Good Environmental Status [35]. The choice of components in a WEC array will alter the environmental noise. Studies concerning the installation of driven piles for windfarm anchors have shown that animal activity was reduced around the construction area, which likely represented a behavioural change rather than permanent hearing damage, although this kind of noise is a potential cause of physical damage to some fish species [38]. In addition, while cables and chains may offer less of a collision risk, they may increase or detrimentally alter the anthropogenic noise around the array [36].

The effects of wave farms on beach morphology and sediment transport are complex and numerous studies are summarised in [35] as part of the SOWFIA project. Taking the case of Wave Hub, a grid-connected area for WEC testing off the coast of Cornwall, the effect on beach

morphology was numerically simulated as part of a study on wave farms as coastal defence tools and a significant effect was found [39]. Conversely, other studies [40] have found that incident wave heights would need to alter by a larger percentage than the 6% predicted [41] for there to be noticeable effects on sediment transport and beach morphology.

In terms of the shared electrical cables (see Section 5.3.6 for more details), sharing underwater components has a potential effect on the construction and geometry of the array infrastructure. Although it has been suggested that cables need not be buried if an appropriate exclusion zone is present [32], electricity carrying cables may need to be buried to mask electro-magnetic effects. If sharing electrical cabling in an array leads to a change in the voltage applied, then the cables may have to be buried deeper than the current standard of greater than 1.5 m below the seabed [35] to avoid electro-magnetic effects causing disruption to marine animals. This would increase cable laying costs.

5.5 Sea space utilisation

The area occupied by an array has implications on both the cost and the performance of the array. Boat traffic is likely to be limited around and within a WEC array [35], so the associated cost of developing a part of the seabed is likely to increase if that area is larger. Furthermore, an important criterion for arrays will be the ability to manoeuvre between the devices for installation and maintenance. The accuracy for anchor deployment is an essential parameter during installation and the safe removal and transportation/towing of devices in an array will be essential for maintenance procedures. Specialist vessels for deployment of wave energy arrays have not been developed yet but examples of existing vessels are given in Table 5-6 on page 41 as part of the cost analysis.

As stipulated in the primary assumptions, Table 4-1, maintenance and access to devices would be facilitated if all the devices of the array can be approached from outside the array. The device should also be sufficiently close in order to create a unique exclusion zone instead of several exclusion zones allowing vessels to operate inside the array. This is shown in Figure 5-11.

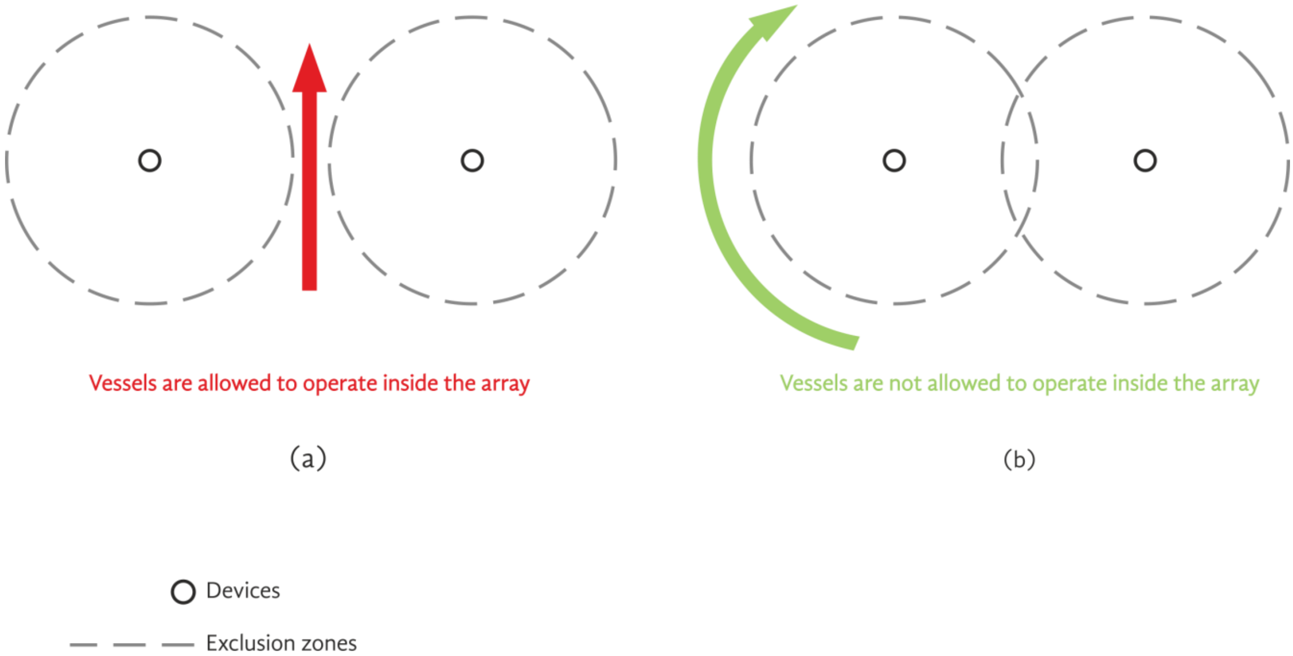


FIGURE 5-11 EXCLUSION ZONES AND ARRAY.

The WEC array being considered as part of this work package comprises only five devices so concessions to exclusion zones will not need to be made. For the die configuration, the centrally placed device can still be accessed with a shallow-draught support vessel since inter-device moorings extend far below the water surface thanks to the clump weight. However, the amount of space that is used at full scale will affect the cost and so is worth considering for the choice of configuration. The footprint of the array configurations also impacts on the physical testing of the devices, Section 6.

The footprint area of the three configurations was calculated by sketching out the likely anchor positions of each inter-moored configuration and calculating the convex hull that surrounds them, Figure 5-12. The convex hull is the smallest convex shape that encompasses all the points in question. The areas of the convex hulls for the full-scale deployments with the spacings as given in Section 5.2.2 and the mooring details as given in Table 5-2 and Table 6-1 are reported in Table 7-1 on page 53.

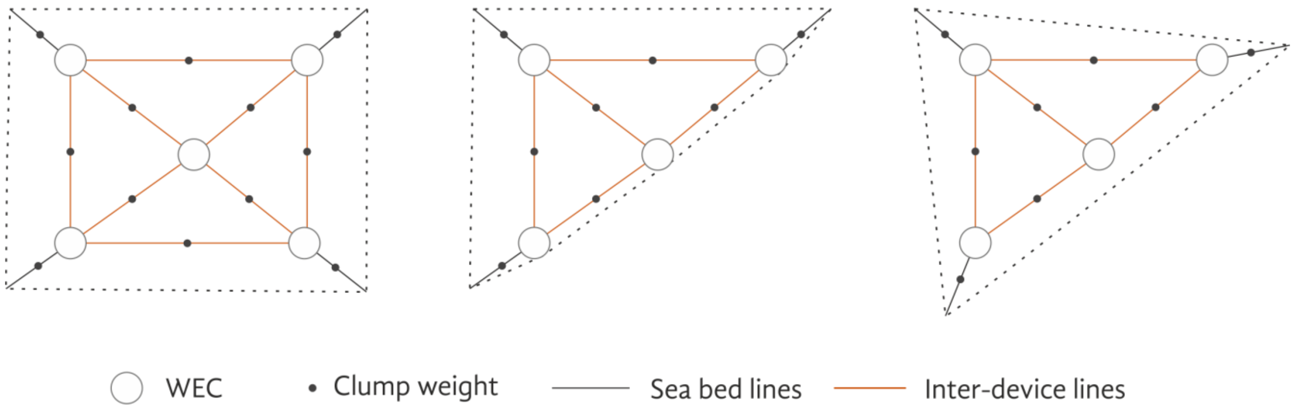


FIGURE 5-12 CONVEX HULL EXAMPLES FOR THE DIE ARRAY: THE FULL ARRAY (LEFT), WITH ONE DEVICE REMOVED BUT SEABED LINES IN THE SAME POSITION (CENTRE) AND WITH ONE DEVICE REMOVED AND RELOCATED SEABED LINES (RIGHT). ARRAY ELEMENTS ARE NOT SHOWN TO SCALE.

6 WP6 Considerations

As shown in Figure 1-2 (page 13), the choice of configurations for both the flexibly and the rigidly connected devices feeds into both the physical and numerical modelling. It is a requirement of the Work Package that the physical experiments be used to validate the numerical simulations but also provide useful information about the device arrays. This means that the choice of configuration has to take into account the constraints imposed by the physical and numerical models, both separately and in conjunction.

As previously mentioned, the electrical cables will not form part of the physical or numerical modelling and are only considered in this document in terms of costs. It is possible that the electrical cables will have some influence on the dynamic response of the OWC spar buoys but the effect of a single riser (cable) is considered to be negligible in comparison to the effects of the mooring lines [42].

6.1 Experimental constraints

The array is to be tested in Plymouth University's COAST Laboratory. The laboratory houses a 35 x 15.5 m wave basin with a variable water depth of maximum 3 m. Table 6-1 summarizes the full-scale and 1:40th model-scale experimental dimensions. To allow the benchmark case of the individually moored devices to fit in the basin at 1:40th scale, with no contact between mooring lines, meaning they cannot cross, some compromises must be made. In order to keep the array spacing constant, truncation of the lines anchored within the central portion of the array may be required to reduce the horizontal scope and affix to the floor below the central device.

For the configurations that do not fit into the width of the basin, a truncation method [43] can be used to reduce the projected horizontal length of the catenary mooring while providing the same restoring forces as the full scale mooring. This is done by splitting the line into a number of different segments and using an optimization algorithm to find the line lengths and masses that give the full-scale restoring force.

TABLE 6-1 FULL SCALE AND MODEL SCALE DIMENSIONS FOR THE PHYSICAL MODEL TESTING

Dimension	1:1 scale	1:40 scale
Device Diameter [m]	12	0.3
Device Draft [m]	48	1.2
Water depth [m]	80	2
Scope [-]	3	3
Seabed Line Length [m]	240	6

The calculated maximum array spacing to avoid collisions is here revised to consider the width of the basin. The pentagon configuration was shown to require an array spacing of 13.3 *D* to avoid collisions with two lines fully taut. With the mooring lengths given in Table 6-1, and with a 13.3 *D*-spacing between the devices, the array would take up 105% of the width of the experimental basin. The spacing required for protection against collisions with one line fully taut would only require 85% of the basin width. It can be shown that the array spacing that would maximise the distance between the devices in the pentagon arrangement and still fit in the basin would be 11.60 *D*, Table 6-2.

TABLE 6-2 COLLISION AVOIDANCE SPACING OF THE CONFIGURATIONS WITH RESPECT TO THE BASIN WIDTH.

Configuration	Two-line collision protection		One-line collision protection		
	Maximum array spacing	% of basin width	Maximum array spacing	% of basin width	Maximised spacing for the basin
Pentagon	13.30 *D*	+5.1%	6.65 *D*	-15.0%	11.60 *D*
Linear staggered	16.50 *D*	+20.1%	8.25 *D*	-11.2%	11.20 *D*
Die	18.80 *D*	-17.7%	9.40 *D*	-35.9%	27.94 *D*

The device spacing was originally constrained to be no less than 6 *D* (Table 4-1) and in Table 5-1 device spacings of less than 10 *D* were shown to lead interaction effects. The full basin spacings of each configuration are all greater than 10 *D* and so interaction effects may not be so pronounced.

6.2 Numerical constraints

The aims of the numerical modelling are to quantify the mooring loads and motions of the devices. The time-domain program OrcaFlex will be used to create the numerical models of the device arrays using lumped-mass theory, with hydrodynamic databases imported from a database calculated by a linear potential flow solver such as NEMOH or WAMIT.

As described in Section 4, OWCs can be modelled as second-order systems and as such, the behaviour of an OWC can be difficult to model. General limitations of the numerical model for a WEC are described in Table 6-3.

TABLE 6-3 GENERAL LIMITATIONS OF DIFFERENT THEORIES FOR NUMERICAL MODELLING OF AN OWC.

	Theory	Hypothesis	Limitations
Moonpool load and PTO		Moonpool and PTO physics will not be modelled accurately. A simple damping model might be used.	Damping value will be calibrated with experimental results (e;g. decay tests) and might not be valid for the whole range of wave period and amplitudes.
Hydrodynamic load on floater hull	Linear Potential Flow	Linear waves: wave amplitude small compared to wavelength	Large waves are out of linear wave scope.
		Wave amplitude small compared to body dimensions	Might not be verified for extreme waves.
		Motion of the body are small relative to body dimensions	Might not be verified for extreme waves.
Mooring lines model	Lumped-mass theory	Elastic lines (linear elasticity)	Synthetic lines may have a non-linear stiffness.
Anchors		Anchors are not modelled and considered as fixed points.	

Within OrcaFlex the internal free surface mode (the piston mode), and the corresponding crossed modes between the structure and the internal free surface will not be modelled. It may be possible to represent the PTO and internal water/air column with an additional damping and to avoid an unrealistic resonance of moonpool and spar motion near resonant pumping mode. However, the numerical model will not model the physics of the internal free surface, thus some inconsistency may remain between simulations and experiments.

Hydrodynamic databases for a given array layout of five spar buoy OWCs will be provided. These databases will be calculated with WAMIT by WAVEC with the OWC chamber open,

without considering the free surface. In particular, 30x30 added mass and radiation damping matrices will be provided. These hydrodynamic databases will be imported into OrcaFlex.

7 Summary and conclusion

Arrays have been identified as part of the WETFEET project as a potential breakthrough area for the wave energy industry. As part of this breakthrough, issues such as high costs, survivability and reliability will have to be addressed in order to advance the industry. This report has considered numerous aspects relating to potential configurations of non-rigid inter-moored devices. Table 7-1 summarises the parameters considered as part of WP6 D6.1.

In terms of the WETFEET WP6 goals, the most important consideration is that the fundamental question can be answered, namely, what scope is there for sharing of mooring lines between nearby devices and how does this affect the performance, cost, survivability, environment and sea-space utilisation. To answer this question the numerical and physical model testing of the die configuration is proposed. Possible interconnection configurations for the die layout are given in Figure 7-1, which shows the baseline case of the individually moored devices and three ways to inter-moor the devices.

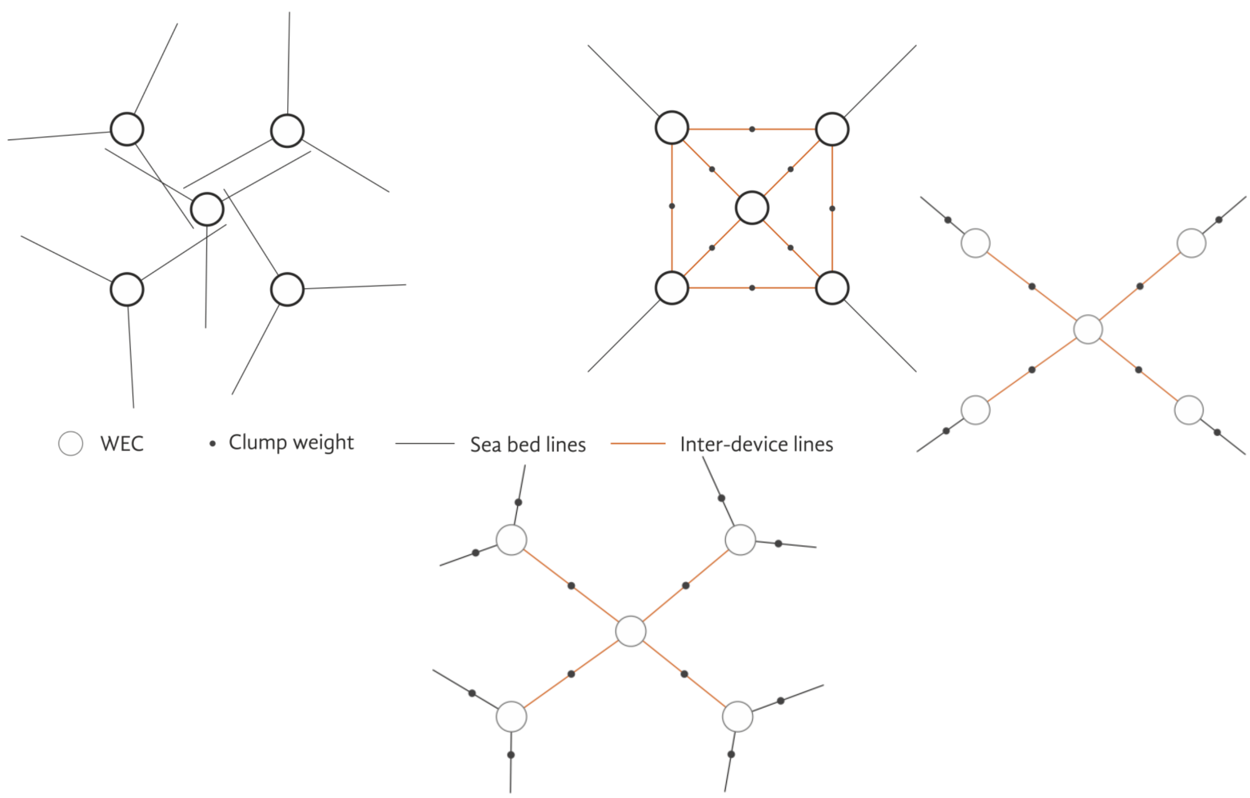


FIGURE 7-1 POSSIBLE ARRAY INTERCONNECTION CONFIGURATIONS FOR THE DIE LAYOUT.

Interaction between the devices in an array has been shown to be important for closely-spaced devices; power production may increase owing to the device interaction depending on the wave climate, device spacing and device in question. The OWC spar buoy was chosen as the test case for this deliverable as it has previously shown promising results.

Table 7-1 shows that there is potential for costs to be reduced when devices in an array are inter-linked and start to share components.

TABLE 7-1 EVALUATION PARAMETERS FOR THE THREE CONFIGURATIONS IN THE MOST INTERCONNECTED STATES AT FULL SCALE.

Parameter	Linear staggered	Pentagon	Die
Design		See Figure 4-4	
Anchors	5	5	4
Seabed lines	5	5	4
Inter-device lines	6	5	8
Clump weights	6	5	8
Anchor cost [GBP k] (1)	583	428	412
Percentage saving on anchors (2)	67%	67%	73%
Line redundancy (3)	1	1	1
Spacing (4) [*D*]	11.20	11.20	9.40
Total seabed area [km^2] (5)	0.16	0.24	0.28
Survivability-peak static load [MN] (6)	12.72	9.33	8.99
Cable architecture cost (7) [EUR k]	285	287	308
Approximate installation cost [EUR M] (8)	57.3	56.5	58.2

(1) Based on an anchor cost of EUR 576/tonne, Table 5-5
(2) Compared to individually moored case
(3) See Section 5.2.3 for details
(4) For one-line taut, no collision as minimum (See Table 5-3, Section 5.2 for details)
(5) See Section 5.5
(6) See Table 5-4
(7) See Figure 5-9
(8) See Table 5-7, Section 5.3.5 for details

The reduction of the seabed lines not only reduces costs but can also mitigate environmental impacts, both on the benthos and marine life. Survivability and sea-space utilisation have also been considered as part of this report. Even with very conservative collision-avoidance spacing, there may be benefits to inter-mooring devices. In terms of the device spacing, there is a trade-off between power density of the array: closer devices will generate more power per unit area of the seabed but collisions between adjacent devices may be more likely and so may drive up the O&M costs.

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9 Appendix

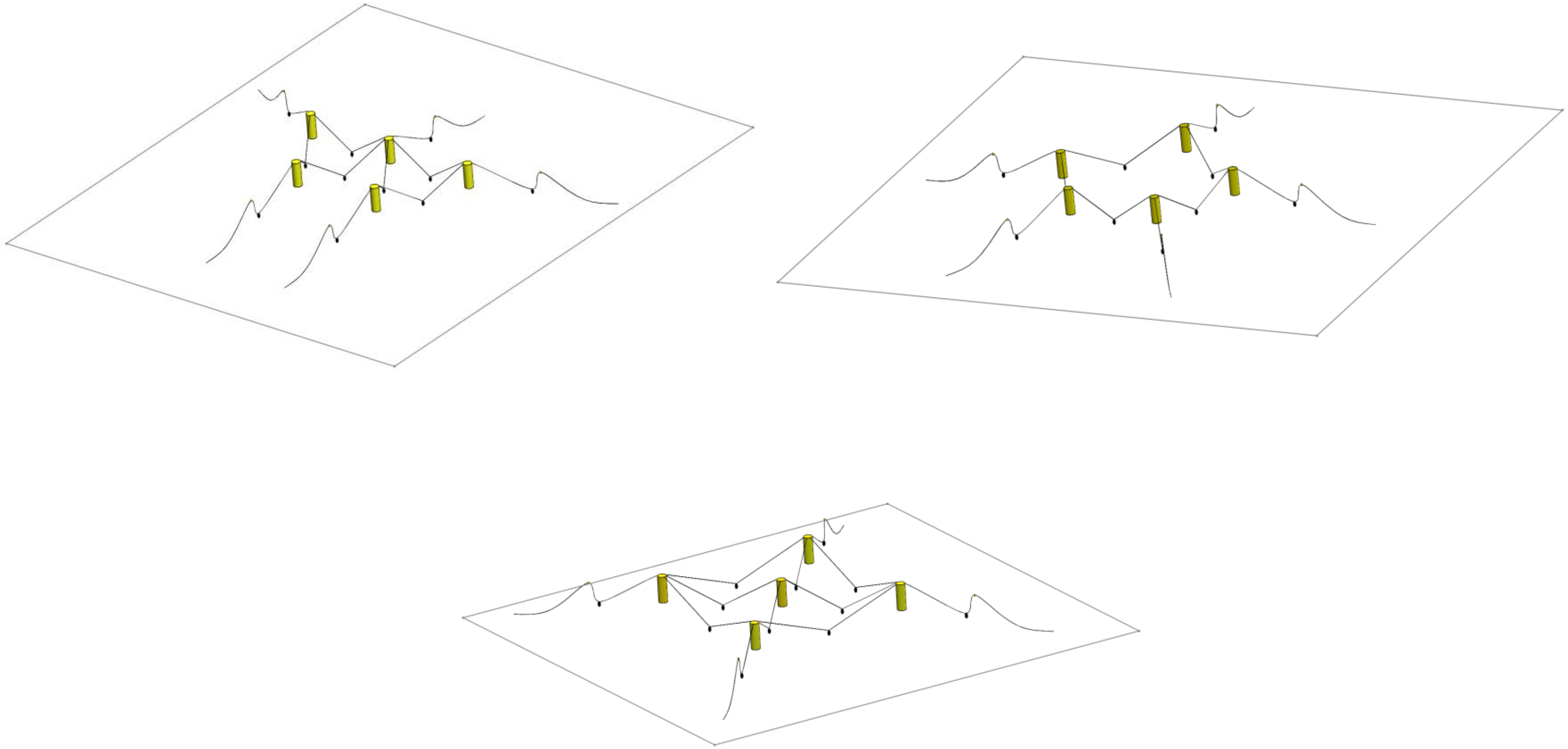


FIGURE 9-1 THREE-DIMENSIONAL VIEWS OF THE THREE ARRAY LAYOUTS IN THE INTERCONNECTED SET UP. DEVICES AND MOORINGS ARE SHOWN TO SCALE BUT WITH DIFFERENT CONSTRAINTS. THE LINEAR STAGGERED (TOP LEFT) AND THE PENTAGON (TOP RIGHT) LAYOUTS ARE SCALED FOR THE BASIN (SEE TABLE 6-2), THE DIE ARRANGEMENT (BOTTOM) IS SCALED FOR THE ONE-LINE COLLISION PROTECTION (SEE TABLE 5-3)

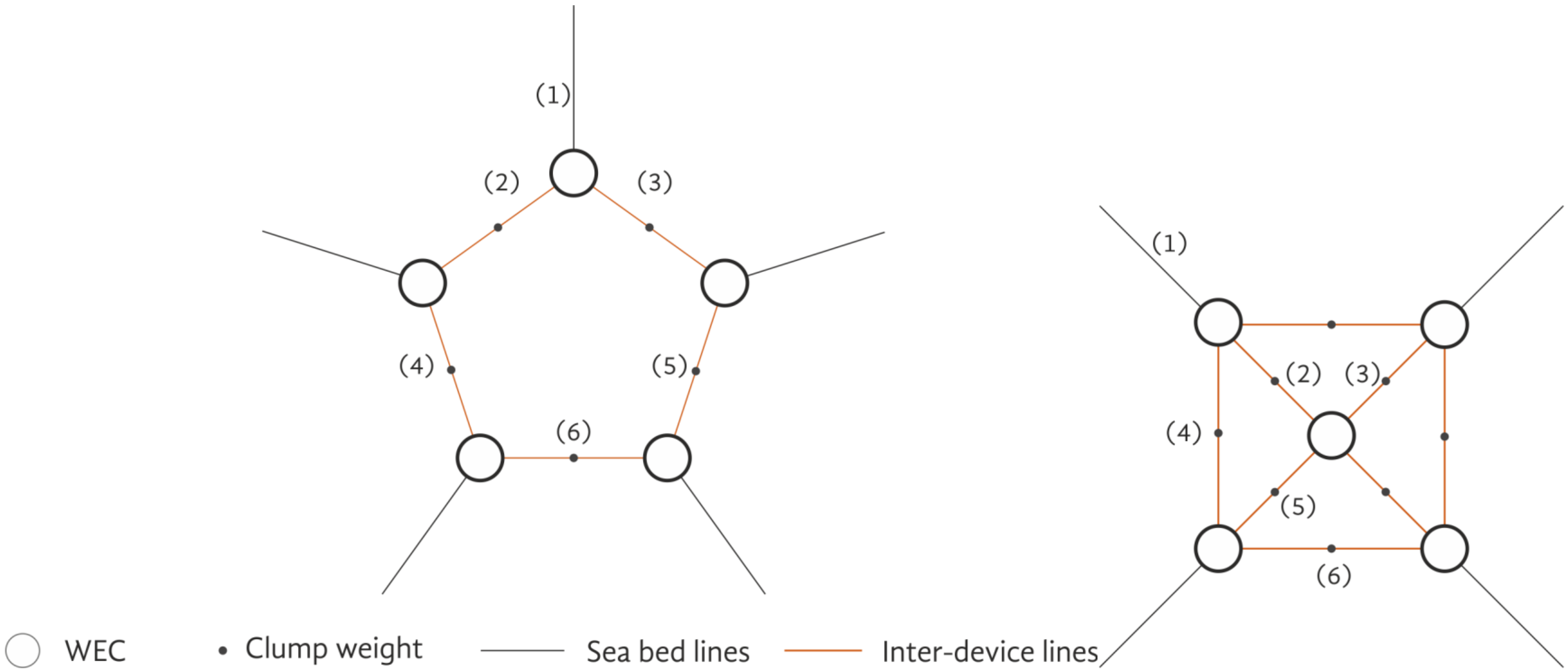
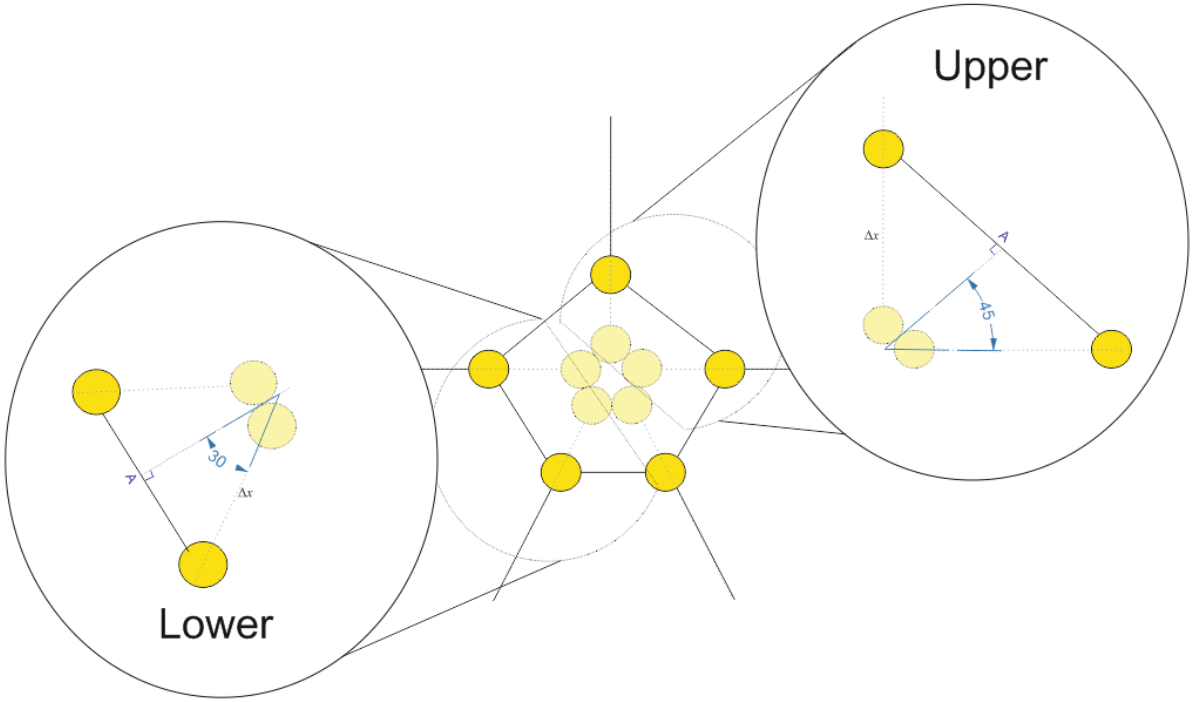


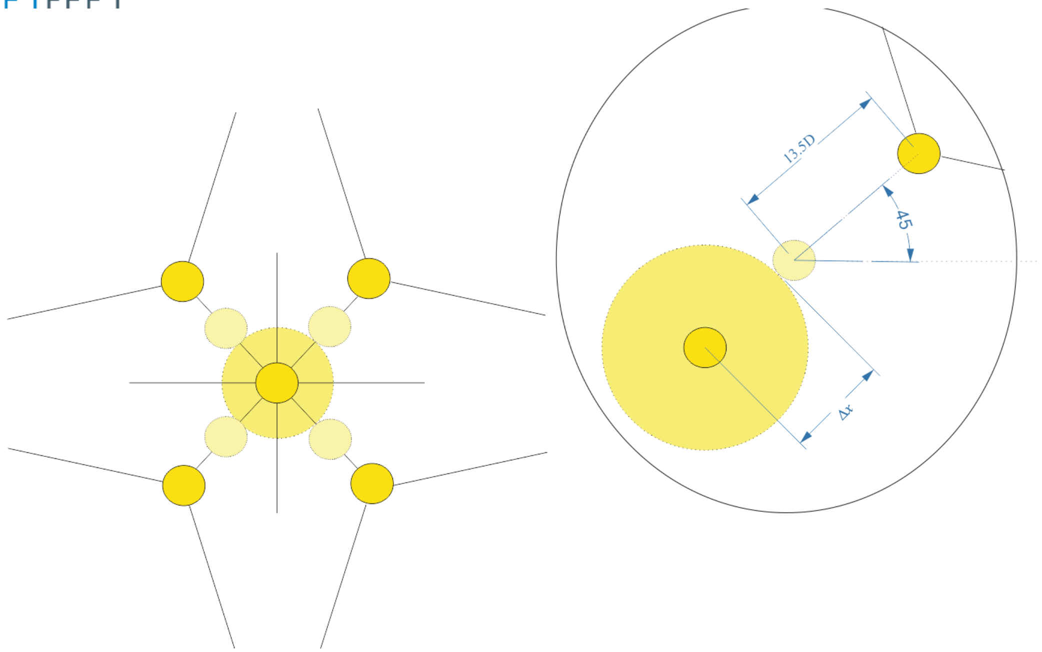
FIGURE 9-2 NUMBERING OF LINES FOR TENSION CALCULATIONS.



$$A_{Upper} = \frac{2 * \Delta x \sin(30)}{D} = \frac{2 * 112.8 \sin(45)}{12} = 13.3D$$

$$A_{Lower} = \frac{2 * \Delta x \sin(30)}{D} = \frac{2 * 112.8 \sin(30)}{12} = 9.38D$$

FIGURE 9-3 DIMENSIONS OF THE PENTAGON CONCEPT SHOWING THE MAXIMUM DISTANCE REQUIRED BETWEEN DEVICES IN THE TOP MOORING LINES.



$$\frac{13.5\text{D} + \Delta \text{x}}{D} = \frac{162 + 112.8}{12} = 23D$$

FIGURE 9-4 FULL COLLISION PROTECTION AT FULL MOORING LINE EXTENSION WITH AN INNER EXCLUSION ZONE FOR THE CENTRAL DEVICE.